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Operational Performance Assessment
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EXECUTIVE SUMMARY



The purpose of this report is to provide an overview of recent Next Generation Air Transportation System (NextGen) improvements and the corresponding operational impacts observed in the National Airspace System (NAS). Our objective is to determine if desired impacts have been achieved, and identify any unanticipated impacts that may also have been realized.

In this report, we focused on a select set of NextGen improvements that were implemented by fiscal year 2013. We included the implementations for which sufficient time has passed for a meaningful analysis to be possible, and for which required empirical data was available in time to complete such analysis.

Localizer Performance with Vertical Guidance Approaches

In 2003, the Federal Aviation Administration (FAA) commissioned the Wide Area Augmentation System (WAAS), which improves accuracy and reliability of appropriately equipped GPS receivers. Unlike traditional ground-based navigation aids, WAAS uses satellites to broadcast its signals, so it covers nearly all of the NAS and is available 99.99% of the time.

Localizer Performance with Vertical Guidance (LPV) is a precision approach procedure that takes advantage of WAAS and provides both lateral and vertical guidance

to the runway threshold. LPV approaches provide Instrument Landing System (ILS) equivalent approach minima to as low as 200 ft without the need for costly ground-based infrastructure. The expected benefits of LPVs depend on the presence of other precision approach capabilities at an airport.

Our analysis of airport-specific operations that were conducted during low visibility weather conditions, and likely facilitated by newly implemented LPV procedures, revealed a significant shift of daytime and Visual Meteorological Conditions (VMC) operations to nighttime and non-VMC operations. Even though demand decreased 1.5 percent on average across the non-ILS airports for which we had a year of data before and after LPV implementations, airport throughput during IMC and marginal VMC increased 22 and 10.9 percent, respectively. Clearly, a significantly higher portion of the overall demand now occurs during the most challenging weather and nighttime, which validates our expectation of improved access to airports under such conditions.

Also, we conducted an analysis of changes in general aviation activity across the NAS to determine whether a change observed at an individual airport with LPV procedures is merely reflective of local trends, or if it suggests increased throughput enabled by recent LPV implementations. Compared to the nearby non-LPV airports, 58% of the airports with an LPV approach and

no ILS capabilities experienced higher general aviation traffic growth, as did 46% of the airports with both LPV procedures and ILS capabilities. These outcomes imply a shift of demand towards airports with better precision approach capabilities. In the absence of ILS, overall general aviation demand grew at a higher rate at the airports with LPV approaches than it did at the nearby airports without ILS approaches.

Required Navigation Performance with Authorization Required Approach Procedures

The FAA has implemented hundreds of RNP approach procedures over the last decade. Utilization of these procedures varies from site to site, driven by both site-specific issues and performance capabilities of the aircraft typically flying in that environment.

Our NAS-wide assessment of RNP approach procedures aimed to determine the differences in performance impacts across a wide range of actual implementations and site-specific operational limitations, and focused on efficiency and predictability impacts and trends. To provide for an accurate estimate of RNP procedure use, we catalogued all of the RNP AR procedures implemented in the NAS through March 2013, and limited our operational impact analysis to only RNP AR approaches with defined turn-to-final.

The average monthly use of RNP ARs with radius-to-fix (RF) turns tripled between 2011 and March 2013. This increase was a result of the new procedures made available at airports with a large number of capable operators and designed to complement the typical flows and approaches of the capable flights.

At some locations, flying an RNP AR approach may result in a less efficient trajectory compared to the alternatives. Overall, however, aircraft that utilized RNP AR approaches with RF turns experienced the best flight efficiency and predictability.

Aircraft that utilized RNP AR approaches with RF turns experienced improvements in performance since 2011, with the most striking improvement in non-VMC conditions, resulting in 3 percent shorter times, 33 percent fewer level-offs, and 42 percent shorter time in level-flight within 60 nm of their destination. These flights were also more predictable, demonstrated by 10 percent lower standard deviations of time and number of level-offs, and a 40 percent lower standard deviation of time in level-flight.

End-to-End Performance Based Navigation

The FAA is implementing advanced Performance

Based Navigation (PBN) procedures to enable suitably equipped aircraft to fly more consistent and direct routes. Area Navigation (RNAV) and RNP procedures and routes have been traditionally implemented to facilitate traffic flows by focusing on individual terminal areas and en route airspace segments. However, in many regions throughout the NAS, aircraft can now fly end-to-end (E2E) PBN routes that connect en route with terminal and approach procedures for a full PBN connectivity. Our analysis aimed to identify differences in performance based on the extent to which aircraft utilize E2E PBN routing.

The corridor between the Pacific Northwest, and California and Phoenix was among the first regions in the NAS with an E2E PBN routing option. We focused on flights from Seattle (SEA) to Oakland (OAK) and from Portland (PDX) to Phoenix (PHX), and categorized them into four categories: Full E2E PBN, Partial E2E PBN, No E2E PBN and No PBN.

Overall, less than 1 percent of flights from SEA to OAK and from PDX to PHX utilized full E2E PBN routing. However, compared to the flights in the other three categories, these flights experienced the best performance, as they proved to be the most efficient and predictable.

Block delay of Full E2E flights from SEA to OAK was 5.7 minutes shorter than that of other flights, and its variance between 10 and 15 times smaller. In the arrival phase, Full E2E PBN flights experienced about one level-off fewer than other flights, and spent up to 2.8 minutes less in level-flight below top of descent.

Flights between PDX and PHX predominantly used E2E PBN routing during peak times. Their flight times were 1 percent shorter compared to Partial and No E2E PBN flights, and 15 percent shorter compared to No PBN flights. These flights were also the most predictable, as the variances of flight times and distances were the lowest across the four PBN categories.

Optimized Profile Descent Procedures at Reagan National and Dulles International Airports

Under the auspices of the Washington Metroplex effort, Optimized Profile Descent (OPD) RNAV STARs were implemented at Reagan National Airport (DCA) and Dulles International Airport (IAD) in August 2012. The procedures, designed to reduce fuel consumption and noise by maintaining a constant and optimal descent angle during landing, provide shorter routes for arrivals from the west to both airports, and facilitate more efficient vertical profiles. In addition, the new STARs also separate DCA and IAD arrival flows, enabling fewer interactions.

Post-implementation analysis of the resulting impacts indicates greater conformance to the procedures, and improved lateral and vertical efficiencies with shorter and more consistent distances and times. The most significant improvements were realized during IMC, when the distance and time flown within 250 nm of DCA and IAD decreased 3 and 5 percent, respectively. Distance and time in level-flight below top of descent (TOD) decreased 30 and 28 percent at DCA, and 19 and 18 percent at IAD.

Finally, the number of level-offs during descent decreased 18 percent for DCA arrivals and 4 percent for IAD arrivals.

Optimized Profile Descent Procedures at Memphis International Airport

Four new OPD RNAV STARs were implemented at Memphis International Airport (MEM) in July 2012. The new procedures were implemented primarily as overlays of existing conventional STARs, but with improved vertical profiles that contain altitude windows facilitating a constant and optimal descent angle during landing.

After implementation of OPDs, utilization of the RNAV STARs increased from 16 to almost 40 percent. The new procedures are utilized to the same extent in both VMC and IMC. Initially, increased conformance to the RNAV STARs caused decreased corner-cutting and, thus, increased the distance and time flown within 250 nm of MEM. However, this negative impact was alleviated by more efficient flows after the implementation of a new wake separation standard, known as RECAT, when we observed a decrease in distance and time of 0.6 nm and 0.21 minutes, respectively.

More significantly, RECAT also facilitated an improvement in arrival flow management, resulting in nearly 50 percent reduction in total holding within 250 nm of MEM, or a savings of over 4,500 minutes in November and December 2012.

In addition, we observed significant efficiency improvements in vertical profiles, with greater benefits realized in IMC when average distance and time in level-flight below TOD decreased 14 and 7 percent, respectively, after the implementation of the OPD STARs, and 26 percent each after RECAT implementation. There were about 2.5 percent more arrivals without level-segments. In addition, we observed a 17 percent decrease in flights with more than three levels-segments after both OPD and RECAT implementations.

Wake Recategorization at Memphis International Airport

Since November 2012, controllers at Memphis Tower are using new spacing criteria to manage separations between aircraft on final approach to, and as they depart from, the airport. Compared to the traditional, the new wake categories provide for more consistency among the aircraft belonging to the same category. As a result, separation standards between successive aircraft can now be safely reduced for many of the same aircraft-pair combinations.

After implementation of the new RECAT spacing criteria at Memphis, the facility set high-end airport rates of 170 operations per hour or higher, about 13 percent more frequently over all weather conditions, and 7 percent more frequently in IMC. High-end arrival and departure rates were not only used more frequently but also increased in magnitude, reaching almost 200 operations per hour.

Airport efficiency improved, driven by tighter aircraft sequences after RECAT. Arrivals are now about 2.5 percent and departures 1.4 percent closer to each other on average as they land and depart from the same runway. During peak arrival and departure periods, the improvement is even higher, reaching 7.5 and 5 percent, respectively.

Together with the new OPD RNAV STARs implemented in July 2012, RECAT also contributed towards improving the efficiency of arrivals in the Memphis terminal airspace. An arrival now flies almost 1 minute shorter time and just under 3 nm shorter distances in the terminal airspace, with high-end savings of 3 minutes and 10 nm, respectively. Arrivals into MEM now fly better vertical profiles, with a 5 percent reduction in flights without level-segments and 2 minutes shorter time in level-flight. All of the terminal efficiency improvements are typically realized within 60 nm of MEM where aircraft are flying at lower altitudes; therefore, the resulting impact on fuel burn was even more positive.

Taxi times for departures also improved. Compared to before RECAT, taxi-out times are now 2.8 minutes or 27 percent shorter during comparable peak departure periods.

New York Metropolitan Area Regional Arrival Performance Analysis

With a goal of improving operations in one of the most heavily congested regions in the NAS, the FAA introduced a series of operational, technological, and

policy changes in the greater New York metropolitan area between 2007 and 2012. Since a significant number of the recent improvements aimed to alleviate problems faced by arriving flights, our regional analysis focused on arrivals, and specifically the four largest airports: Newark International Airport (EWR), John F. Kennedy International Airport (JFK), LaGuardia Airport (LGA), and Philadelphia International Airport (PHL). Our analysis aimed to determine overall impacts throughout the New York metropolitan region.

Since January 2011, there has been a considerable reduction in both times and delays across all phases of flight for arrivals into the largest four airports in the area. By the end of 2012, total vector delays were 41 percent lower and hold durations 51 percent lower. On average, taxi-in times decreased 0.6 minutes for arrivals into New York, while the gate delays and taxi-out times at origin airports decreased 1 minute and 3.1 minutes, respectively. Actual block times were 1.4 minutes lower and block delays 1.9 minutes lower on average.

This analysis represents a first step in a comprehensive assessment of performance impacts in the New York metropolitan area. In the future, we will complete the regional assessment by investigating the impacts on departures.

Separation Reduction in New York Low-altitude Airspace

Single-site radar procedures, which support a reduction in required separation from 5 nm to 3, were implemented in twelve sectors with airspace below 18,000 ft in the New York Air Route Traffic Control Center (ZNY). The new aircraft separation policy was implemented in stages, with the largest and final state completed in May 2011.

We would expect the reduction in minimum separation to allow controllers to put aircraft closer together, resulting in more efficient flight paths. After the implementation of the new separation policy, we did indeed observe aircraft flying closer to each other, with about 9 percent more frequent occurrence of being within 1,000 ft vertically, 7 nm laterally and 5 seconds from each other. While waiting to enter low altitude ZNY sectors, flights now experience 20 percent shorter holding durations as well as a 19 percent savings in excess time due to vectoring. The most significant impact on vectoring was realized in the airspace feeding the sectors affected by the new policy, especially in sectors that predominately handle departure and crossing flows. However, the impact on vectoring was not statistically significant within the sectors directly affected by the separation reduction.

Lower Runway Visual Range Minima Operations and Simultaneous Offset Instrument Approaches at San Francisco International Airport

Low visibility and clouds at San Francisco International Airport (SFO) often restrict arrivals and departures. Recently, the FAA introduced improvements enabling a reduction of Runway Visual Range (RVR) minima for departures and cloud ceiling minima for Simultaneous Offset Instrument Approach (SOIA) arrivals at the airport. As a result, SFO can now provide services during low visibility conditions not possible in the past, and use two active runways when previously limited to only one.

After the January 2011 reduction of RVR minima to enable SFO dual runway operations, high-end departure throughput during visibility of up to 0.25 miles has been recorded and sustained for longer periods. Hourly departure throughput weighted by the actual duration of low visibility conditions increased 12 percent, and the overall airport operations rate weighted by the actual duration of low visibility conditions increased by 14 percent.

Since the SOIA procedure amendment in September 2012, SFO has been accommodating about 16 percent higher arrival throughput during the periods with cloud ceilings between 1,600 ft and 2,100 ft lower minima. Compared to the performance observed in the equivalent conditions between 2010 and 2012, the frequency of holding arrivals during adverse weather is now 23 percent lower, and the holding delay 8 percent shorter.

Converging Runway Display Aid at Boston Logan International Airport

Terminal controllers use an automation tool known as Converging Runway Display Aid (CRDA) to help space aircraft arriving on converging runways. The tool allows controllers to easily visualize and direct a safe and efficient separation distance between aircraft by projecting the flight position from one approach path onto the straight-in final approach path of the other aircraft.

Although CRDA is available in all terminal automation systems, its adaptation is site specific. Few airports have been able to implement CRDA due to the complex and costly design analysis required to address all of an airport's operational considerations. CRDA has been adapted for routine operations at Boston Logan (BOS), Philadelphia, Memphis and Newark Liberty airports.

The September 2012 implementation of CRDA at BOS enabled dual runway operations during IMC, and when the tailwinds exceed 3 knots. With CRDA, BOS can

now accept arrivals to both runways 22L and 27, and accommodate up to 38 arrivals per hour. This 19 percent increase provides BOS with enough gain in effective capacity to handle demand during the busiest periods, and frequently eliminates the need to implement a ground delay program (GDP).

While CRDA use is rare, the savings it enables are substantial. Per Boston TRACON logs, CRDA was used nine times for a total of 23 hours. This eliminated the need for GDPs for 104 flights and resulted in an estimated savings of 53 hours of Estimated Departure Clearance Time (EDCT) delays. CRDA is likely to yield greater benefits by reducing GDP use and corresponding delays as facilities begins to use it on a routine basis.

Precision Departure Release Capability

Developed by NASA, the Precision Departure Release Capability (PDRC) system improves tactical departure scheduling by reducing the uncertainty of en route entry times. Based on existing technology, the system includes surface and en route automation tools that improve the

accuracy of wheels-off and airborne time estimates, and a two-way communication interface that enables coordination and communication of departure release times.

NASA researchers evaluated the PDRC system through three field evaluations at NASA's North Texas Research Station. The first evaluation was an initial shadow operation to investigate the feasibility of the concept. During the two field evaluations, controllers used the PDRC to schedule 238 flights over a period of 29 weeks.

Center and TRACON controllers provided positive feedback about the PDRC system. PDRC delivered more accurate wheels-off and airborne time estimates, resulting in improved meter fix capacity management, and more efficient merging of departures into the overhead enroute flows.

In August 2013, NASA formally transitioned the PDRC system to the FAA for further development and implementation.

Introduction



The Next Generation Air Transportation System, or NextGen, is transforming the way things work in our nation's skies and airports. We are overhauling our National Airspace System (NAS), shifting from radar to satellite-based technology to guide and track air traffic more precisely. We are creating an even more predictable system that reduces delays from gate to gate.

There are three key documents the FAA's Office of NextGen publishes annually to communicate its plans and achievements of NextGen. The first two are the NextGen Implementation Plan and the Business Case for NextGen. They provide an overview of the FAA's ongoing transition to NextGen and an overview of the FAA's cost-benefit assessment of the air traffic management aspects of NextGen. This report is the third key document, the Annual NextGen Operational Performance Assessment.

The purpose of this report is to provide an overview of

recent NextGen improvements and the corresponding operational impacts observed in the NAS. Our objective is to determine if desired impacts have been achieved and identify any unanticipated impacts that may also have been realized.

In this report, we focused on a select set of NextGen improvements implemented by fiscal year 2013. We included the implementations for which sufficient time has passed for a meaningful analysis to be possible and for which required empirical data was available in time to complete such analysis.

In the following chapters, we provide a summary of our statistical analysis, and describe the operating environments of airports and other locations where we placed enhancements into the field. As was the case with our prior annual assessments, our aim is to measure the impacts of deployed NextGen capabilities in a systematic and standardized way.

Localizer Performance with Vertical Guidance Approaches



In 2003, the FAA commissioned the Wide Area Augmentation System (WAAS), which provides augmentation information to GPS receivers to enhance their accuracy and reliability. Unlike traditional ground-based navigation aids, WAAS uses satellites to provide coverage to most of the National Airspace System (NAS), and is available 99.99 percent of the time.

Localizer Performance with Vertical Guidance (LPV) is a precision approach procedure that takes advantage of WAAS and provides both lateral and vertical guidance to the runway threshold. LPV approaches provide Instrument Landing System (ILS) equivalent approach minima to as low as 200 ft without the need for costly ground-based infrastructure. Actual minima for an LPV approach are based on the airport's current infrastructure, as well as an evaluation of existing obstructions. The benefits of LPVs depend on the presence of other precision approach capabilities at an airport. For airports with an existing ILS, an available LPV approach:

- To the same runway end provides multiple options for landing on that runway, and can serve as the primary approach when the ILS is out of service or unavailable; and
- To a different runway end provides an alternate landing option, especially when winds necessitate the utilization of secondary runways.



Figure 1 – LPV Availability in the Continental U.S.

For airports with no existing ILS, an LPV approach is even more beneficial since it:

- Provides access during instrument meteorological conditions (IMC) and marginal visual meteorological conditions, and when ceiling and visibility are lower than the requirements for visual meteorological conditions (VMC) or below existing minima for an airport's instrument approach procedures (IAP) such as Localizer, Non-directional beacon (NDB) or VHF Omnidirectional Range (VOR);
- Allows an airport to serve as an alternate when conditions worsen at a nearby destination airport with no precision approach capability; and

- Facilitates greater confidence and increased comfort levels for pilots flying into these airports, especially during night operations and in IMC and marginal VMC when ceiling and visibility are close to procedure minima.

As of April 2013, there were more than 3,100 WAAS LPV approaches in the U.S.¹ Fig. 1 displays the airports with implemented LPVs in the continental U.S. as of November 2012. LPV approaches can be executed in any aircraft equipped with a WAAS-enabled GPS (e.g., Garmin GNS430W, GNS480) that is certified for Instrument Flight Rules (IFR). The approaches are similar to other IAP and can be executed by any instrument rated pilot. No other special air crew training is necessary. LPV approaches are predominantly utilized

Digital Aeronautical Flight Information File (DAFIF) and graphical aeronautical charts.

Weather information — needed to infer periods of LPV use — is available for most airports through Meteorological Routine Aviation Weather Report (METAR) or Automated Surface Observation System (ASOS). However, throughput analysis for most small airports is limited due to the sparse availability and limited granularity of operational data in official sources such as Aviation System Performance Metrics (ASPM), Operations Counts (OPSNET), Air Traffic Activity Data System (ATADS) and Terminal Area Forecast (TAF). TAF provides annual historical operations, and includes forecasts for itinerant and transient operations by user class. Some of the operations included in TAF are not

Weather conditions: ceiling and visibility below 1,000ft and 3sm, respectively

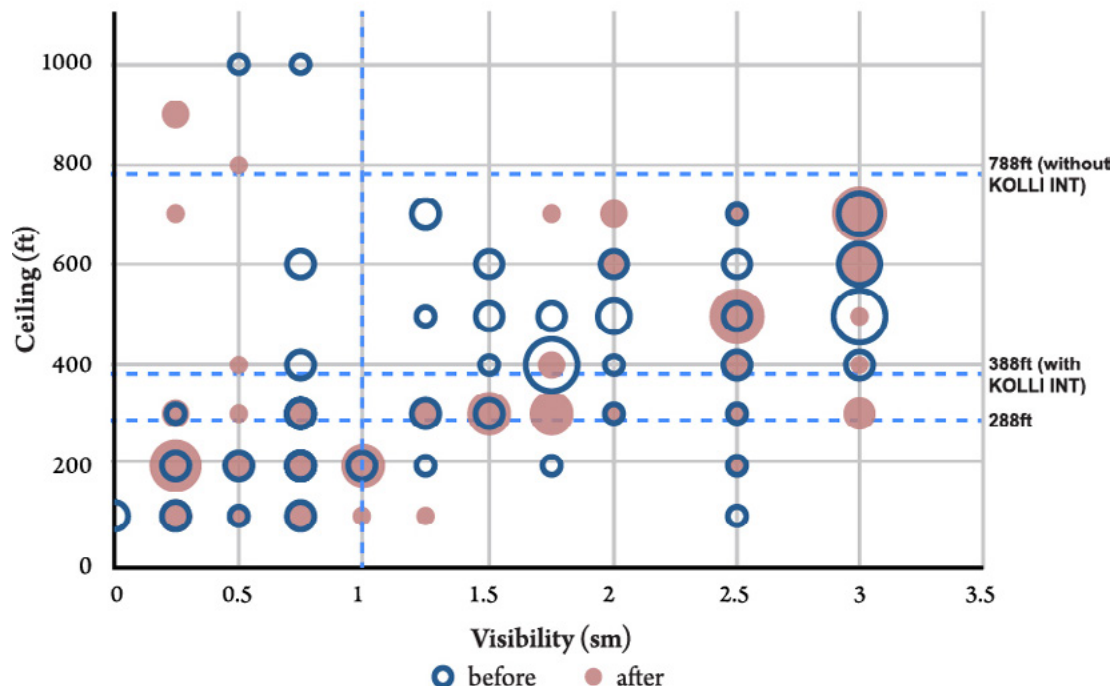


Figure 2 – Comparison of Arrivals into CDW before and after LPV Implementation

by general aviation pilots and a few commercial carriers, including Horizon Air and Cape Air.

Currently, there is a lack of empirical data on the utilization of specific approach procedures. In the absence of such data, utilization can be inferred by comparing actual trajectories to the procedure definitions. This requires four dimensional (4D) trajectory data for flights in the airport terminal area, which is available in Traffic Flow Management System (TFMS) or National Offload Program (NOP) databases for most major airports. TFMS and NOP contain all flights that are under active air traffic control (ATC). Terminal procedures are available in digital form in the National Flight Database (NFD),

under active air traffic control and, therefore, are not included in TFMS or NOP data.

There are two key challenges to estimating the utilization of LPV procedures:

- 1) Surveillance data and 4D trajectories frequently do not include the last miles flown by an aircraft before touchdown, particularly at small general aviation airports; and
- 2) LPV approaches are typically designed as 'straight-in' paths, which often overlap other procedures and, therefore, are not distinguishable from them. A flight's

use of an LPV procedure can sometimes be surmised from airport weather conditions at the time of arrival. However, even where data is available, gaps and inconsistencies may hinder analysis.

For example, unless special weather conditions necessitate more frequent updates, METAR data is archived hourly, which does not provide the granularity in ceiling and visibility observations needed for this analysis. Further, the weather conditions during which an LPV approach might improve airport access over existing alternatives, and the number of operations at most general aviation airports under those conditions, are often too infrequent to support conclusive findings.

The challenges to conducting LPV analysis are illustrated in Fig. 2, which shows the number of arrivals into Essex County Airport (CDW) in Caldwell, N.J., when the prevailing weather conditions were below 1,000 ft ceiling and 3 statute mile (sm) visibility. Arrivals are plotted by ceiling and visibility in blue for the pre-implementation period, and red for the post-implementation period. The size of the symbol represents the number of arrivals, ranging from the smallest symbol of one to the largest symbol of nine, during different operating conditions as defined by visibility and ceiling.

Prior to the implementation of the LPV approach at CDW, the existing NDB provided minima of 1 sm visibility and 788 foot ceiling when not using the KOLLI intersection, and 388 ft otherwise. The new LPV procedure provides minima of 288 ft and 1 sm visibility, a reduction in ceiling of only 100 ft. As evident from Fig. 48, the precision of meteorological data is not sufficient to support a post-implementation analysis of improvements in airport access during the LPV-enabled weather conditions.

This ambiguous outcome underscores several limitations in conducting LPV analysis:

- Surface weather reporting systems were never intended to provide the precision need for this kind of analysis. Weather readings from METAR and ASOS are in 100s of feet, while ceiling requirements are not necessarily defined in 100-foot increments. Discrepancies and gaps in weather data, in addition to the time interval between weather observations, further limit our analysis.
- The difference in decision height and visibility minima can be too small to clearly identify corresponding performance impacts, such as 388 ft versus 288 ft in the example above.
- The best available source of aircraft arrival times is TFMS arrival messages (AZ). However, AZ messages do not always capture the exact touchdown time.

Also, changes in meteorological conditions may not be instantaneously updated in METAR or ASOS. As a result, archived ceiling and visibility conditions associated with the actual time of arrival may not be accurate.

- General aviation pilots are not prohibited from landing when reported ceiling and visibility are below prescribed procedure minima.
- There could be other precision approaches, such as Localizer with Directional Aid, with minima lower than those of an LPV procedure.
- The actual runway and procedure used are unknown, and often cannot be estimated by evaluating conformance of the actual trajectories to the published procedures because of insufficient granularity of and gaps in surveillance data. Therefore, the applicable minima cannot be determined accurately when several procedures exist for a given airport.

Operational Performance Assessment

These limitations notwithstanding, we investigated the impact of LPV implementations with the available data. In order to analyze the operational performance impacts of recently implemented LPV approaches, we examined changes in arrival throughput as indicators of increased access to airports, especially during IMC, and low visibility and low ceiling conditions. However, since arrival throughput is highly dependent on overall demand, we were not able to conclusively estimate impacts at many of the locations that were included in the study.

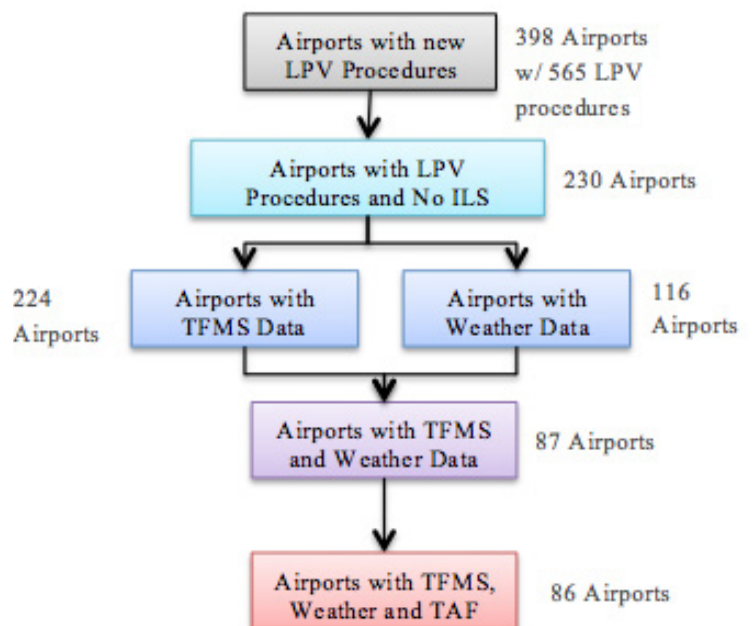


Figure 3 – LPV Airports with Available Data

Therefore, we also examined the change in demand at airports with LPV procedures relative to the change in demand at nearby airports without any LPV procedures. This analysis aimed to inform whether changes in total general aviation activity were merely reflective of local aviation demand, or if they suggest increases in throughput enabled by recent LPV implementations.

Our analysis of general aviation airport access as a function of weather focused on airports where LPV procedures were implemented between January 2011 and August 2012. This timeframe enables analysis of the most recent implementations where the new procedures have been available for at least 6 months. As depicted in Fig. 3, there were 565 LPV procedures implemented at 398 airports during this period. About 42 percent of these airports also have an ILS approach, and the key benefit the new LPV procedures enable at these sites is improved flexibility, which is very difficult to quantify. In addition, at most of these sites, the LPV procedures overlap to a high extent with the ILS approaches. Combined with data gaps, the inability to accurately identify which procedure was actually used undermines any performance assessment.

Of the remaining 230 non-ILS airports, annual demand, surveillance and weather data are reported and archived for only 86 airports. Due to large gaps in weather data that spanned several months, we had to exclude 15 other airports from our detailed analysis of arrival rates under varying weather conditions.

For the remaining 71 airports in our study, we evaluated and compared operational performance before and after LPV implementation based on their individual publication dates. For procedures implemented prior to March 2012, we were able to work with a full year of data before and after implementation, and account for seasonal effects that may have also affected airport demand and throughput. This data applied to 54 of the 71 airports.

For procedures implemented between March 2012 and August 2012, we worked with all available data for the post-implementation period and based our assessment of pre-implementation performance on the same months from the previous year. Using this approach, we were able to account for variability of general aviation demand across at least 6 months before and after implementation, but were not able to account for seasonal effects. Therefore, we present outcomes and findings for the 71 airports included in the analyses as well as separately for the sites with a full year of post-implementation data.

We used 2010 and 2011 TAF data to determine changes in total annual throughput as an indicator of changes in demand, TFMS arrival messages to observe changes in throughput by time of day, and METAR data to determine weather conditions at the airport at the time of each flight's arrival.

We started our analysis by evaluating demand and arrival rates at the 71 airports, and comparing the outcomes we observed before and after LPV procedures were published. Fig. 4 provides scatter plots of the changes in average hourly arrival rates observed during day and night for all weather conditions, and for IMC and marginal VMC. It also highlights airports that experienced more significant increases in operations: Arlington Municipal Airport (AWO), Arlington, Wash.; Beaver County Airport (BVI), Beaver Falls, Pa.; Clinton-Sampson County Airport (CTZ), Clinton, N.C.; Decorah Municipal Airport (DEH), Decorah, Iowa; Duplin County Airport (DPL), Kenansville, N.C.; Weedon Field Airport (EUF), Eufaula, Ala.; Mobridge Municipal Airport (MBG), Mobridge, S.D.; Midland Airpark (MDD), Midland, Texas; Martin State Airport (MTN), Baltimore; Waupaca Municipal Airport (PCZ), Waupaca, Wis.; Ruston Regional Airport (RSN), Ruston, La.; and Avenger Field Airport (SWW), Sweetwater, Texas.

Most of the airports experienced no change or an

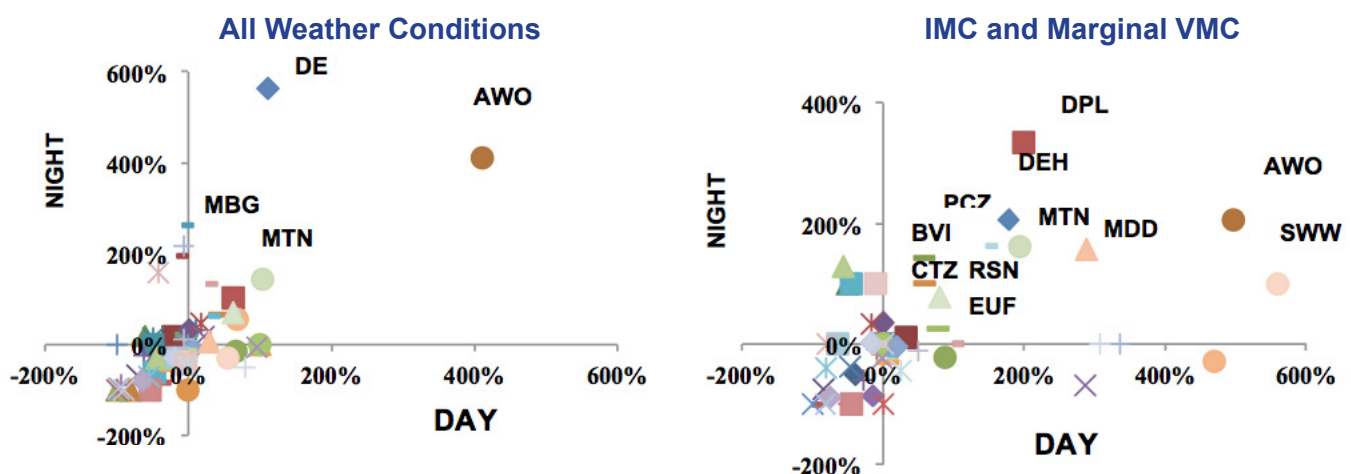


Figure 4 – Changes in Average Hourly Throughput after Implementation of LPV Procedure

increase in the number of flights under active ATC. However, an increase in airport throughput may simply be a sign of increased demand for services rather than a conclusive sign of improved access, so we had to conduct more detailed analysis and focus on specific relevant operating conditions to determine any possible correlation to LPV implementations.

Across the 71 airports, demand decreased by 1.3 percent on average in the post-implementation period, while the total number of flights under active ATC increased by 4 percent during all weather conditions. The time in IMC and marginal VMC weather conditions was lower by 5.7 and 13.5 percent, respectively. However, as shown in Table 1, the aggregate number of flights in those conditions increased by 13.1 and 2.9 percent, respectively. While inconclusive, this simultaneous decrease in overall demand, along with an increase in operations during IMC and marginal VMC, suggests that improved confidence among pilots in accessing these airports under poor weather conditions is attributable to a precision IAP such as the LPV procedure.

Despite the net decrease in demand, we observed significant increases in throughput during the most challenging weather and night conditions. These outcomes further validate our expectation of improved access to airports under such conditions due to the confidence that pilots gain with the availability of a precision approach. Precision approaches enable operations in poor weather and increase the safety of night arrival operations in all weather. These considerations are especially important at airports with terrain and other obstructions in close vicinity.

While these outcomes cannot be used to definitively attribute improved performance in poor weather and night conditions to the LPV implementation, it is important to emphasize that the airports included in this analysis did not have ILS. Thus, it is likely that the new procedures did facilitate the operations observed during these conditions. We can infer that LPV implementations provided benefits by contributing to a significant shift in operations from VMC to IMC and marginal VMC, especially since we observed this shift not only during day but also during night.

Table 1 – Summary of Changes for Selected Outcomes for All 71 Airports

Outcome	Total	VMC	IMC	MVMC	Low Ceiling ¹	Low Visibility ²
Number of Arrivals	4.0%	3.7%	13.1%	2.9%	-6.2%	-6.5%
Time in Specified Weather Conditions		4.2%	-5.7%	-13.5%	-0.3%	52.9%

¹ Ceiling below minima required prior to LPV implementation

² Visibility below minima required prior to LPV implementation

As shown in Table 2, across the 54 airports with one year of data after LPV implementation we observed an average decrease in demand of 1.5 percent, and a net increase in total operations under ATC control of 0.6 percent. Total operations increased 1 percent during the day and decreased 1 percent at night. Here too, the changes under IMC and marginal VMC are noteworthy. While the occurrence of IMC and marginal VMC decreased by 4 and 12.9 percent, respectively, the number of arrivals increased by 22 and 10.9 percent in each condition. These changes include sizable increases during night conditions, and contrast with the reductions observed under VMC in both day and night operations.

In the post-implementation analysis described to this point, we examined airport-specific changes in arrival throughput during specific weather conditions as indicators of LPV-related performance impacts. In addition, we performed a separate analysis to assess the changes in airport throughput after the implementation of LPV procedures in the context of local demand trends. The latter analysis informs whether the changes in total general aviation activity are merely reflective of local aviation demand, or if they suggest increases in throughput enabled by recent LPV implementations. Airports where post-implementation traffic growth exceeds the traffic observed at nearby, non-LPV airports over the same comparison periods may reflect this

Table 2 – Summary of Changes for Selected Outcomes for 54 Airports with Full-Year Data

Outcome	Total	VMC	IMC	MVMC	Low Ceiling ¹	Low Visibility ²
Number of Arrivals	0.6%	-1.2%	22.0%	10.9%	-3.3%	-15.2%
Number of Day-time Arrivals	1.0%	-0.8%	22.9%	13.4%	-2.4%	-19.1%
Number of Night-time Arrivals	-1.0%	-3.3%	20.2%	4.1%	-4.7%	-10.4%
Time in Specified Weather Conditions		6.6%	-4.0%	-12.9%	1.5%	35.0%

¹ Ceiling below minima required prior to LPV implementation

² Visibility below minima required prior to LPV implementation

Table 3 – Filtering of LPV Airports for Analysis

Airport Set	LPV	
	Airports	Procedures
Airports with LPV procedures	1,550	3,106
ATADS airports with LPV procedures	449	1,251
ATADS airports with LPV procedures and at least one nearby non-LPV airport	112	299
ATADS airports with LPV procedures, at least one nearby non-LPV airport, and 12 months of data before and after LPV implementation	94	257

impact from LPV procedures. To the degree that we observe this by a majority of airports within the study sample, we can strengthen our confidence in such a finding.

Since overall traffic growth, including VFR, was critical to this analysis, we decided to use ATADS as the source of air traffic operations. This data includes IFR and VFR itinerant operations and local operations by airport, and is reported monthly. As summarized in Table 3, there were 449 airports in ATADS that had at least one LPV procedure published as of April 2013, and 75 airports without any LPV procedures. One hundred twelve of the 449 airports with LPV procedures were located within 50 nautical miles (nm) of at least one airport without LPVs. The 50-nm radius, while subjective, was deemed appropriate for inferring exposure to similar aviation demand drivers and for capturing possible demand “spill” effects due to airport-specific changes. Eighteen of the 112 airports did not have any general aviation operations in each of the 12 months immediately preceding and following the earliest LPV implementation. As a result, we were able to examine trends at only 6 percent of all airports with LPV procedures, or 21 percent of ATADS reporting airports with LPV procedures.

We measured the change in general aviation traffic at each LPV airport as the ratio between the total number of operations observed during the 12 months before and after implementations around the date of the initial LPV publication. Values between zero and one indicate less demand in the post-implementation period, while values greater than one reflect growth. Similarly, we calculated the demand change ratios for each airport’s nearby, non-LPV counterpart(s) during the same time. The difference in ratios between an airport with an LPV procedure and its non-LPV peers reflects the relative change in general aviation throughput, with positive values indicating higher growth or a smaller decrease than at the non-LPV reference airport. Assuming that neighboring airports would otherwise exhibit similar demand trends, we can conclude that positive values in this difference imply higher demand as a result of improved airport services, including LPV procedures.

In Table 4, we present the distribution of airports with LPV procedures by availability of ILS and change in

general aviation traffic relative to their non-LPV peers. Only 12 of the 94 LPV airports, or 13 percent, in the study do not have ILS capabilities. These airports are the most likely to exhibit LPV-related increases in general aviation traffic, as discussed previously.

Table 4 – Distribution of Airports with LPV Procedures by Availability of ILS and General Aviation Traffic Growth

ILS at Airport?	Number of airports with LPVs where general aviation traffic growth after implementation is:		Total
	HIGHER than at nearby airports w/o LPVs	LOWER than at nearby airports w/o LPVs	
No	7	5	12
Yes	38	44	82
Total	45	49	94

In terms of their relative traffic growth, we found a fairly even split of the airports in this study. Forty eight percent of the airports with LPV procedures experienced an increase and 52 percent a decrease in general aviation operations compared to their nearby counterparts without LPVs.

However, when airports are grouped by availability of ILS, the performance of LPV airports relative to their non-LPV peers appears to align more closely with expectations. Table 5 presents traffic growth ratios for each of the 12 non-ILS, LPV airports and their nearby, non-LPV counterparts. Compared to the nearby non-LPV airports, 58 percent of the airports with an LPV approach and no ILS experienced higher general aviation traffic growth. By contrast, 46 percent of the airports with both LPV procedures and ILS exhibited higher traffic growth than their non-LPV counterparts.

While these outcomes are based on a small sample of relevant airports and may not be considerably different from each other, they do imply a shift of demand towards airports with better precision approach capabilities. In the absence of ILS, overall general aviation demand grew at a higher rate at the airports with LPV approaches than it did at the nearby airports without ILS approaches.

Ultimately, the small sample size in this analysis limited

Table 5 – Airports with LPV Procedures and No ILS included in Study

LPV Apt.	Airport Name & State	Number of nearby Non-LPV Airports	Traffic Growth Ratio		Diff.
			LPV apts.	Non-LPV apts.	
HWD	HAYWARD EXECUTIVE, CALIFORNIA	2	1.20	1.00	0.19
OWD	NORWOOD MEMORIAL, MASSACHUSETTS	1	1.13	0.96	0.17
EVV	NEW SMYRNA BEACH MUNI, FLORIDA	1	1.14	0.98	0.16
DVT	PHOENIX DEER VALLEY, ARIZONA	4	1.18	1.09	0.08
HHR	JACK NORTHROP FIELD/HAWTHORNE MUNI, CALIFORNIA	6	1.03	0.95	0.08
CMA	CAMARILLO, CALIFORNIA	4	0.99	0.94	0.05
WJF	GENERAL WM J FOX AIRFIELD, CALIFORNIA	4	0.99	0.96	0.03
RNT	RENTON MUNI, WASHINGTON	1	0.79	0.81	-0.02
RHV	REID-HILLVIEW OF SANTA CLARA COUNTY, CALIFORNIA	2	0.96	1.06	-0.11
PMP	POMPAHO BEACH AIRPARK, FLORIDA	1	1.05	1.20	-0.15
GEU	GLENDALE MUNI, ARIZONA	4	0.89	1.08	-0.18
BCT	BOCA RATON, FLORIDA	1	1.03	1.23	-0.20

our ability to remove the effects of many drivers of general aviation demand. While the results are consistent with expected impact of LPVs, our confidence in these findings would be raised by addressing data gaps to expand the set of airports in the study.

Conclusions

A comprehensive understanding of operational performance impacts and benefits of LPV implementations is limited by significant data gaps. Empirical data on procedure utilization is not available, and cannot be accurately estimated across the NAS for two key reasons. First, LPV procedures are rarely distinguishable from other procedures that may be available at the same location. Second, surveillance data frequently does not include aircraft activity within the last miles of an airport. In addition, there are limitations in archived aviation weather data, including locations and periods for which the data is recorded, as well as the precision of the data. Finally, airport access is not only driven by the ease of access but also by the demand for services, which is typically both inconsistent and below capacity at general aviation airports. As a result, it is difficult to definitively attribute any changes in performance to the newly available capabilities at general aviation airports. However, we found several indicators that do suggest improved performance at many of the airports we were able to include in our analysis.

Our analysis of airport-specific operations during low visibility weather conditions revealed a significant increase in nighttime and non-VMC operations, likely facilitated by newly implemented LPV procedures. The increases occurred despite pronounced decreases in the frequency of occurrence of these conditions. Significantly, we observed increases in nighttime as well as daytime. Collectively, these outcomes support our

expectation of improved access to airports under such.

Also, we conducted an analysis of changes in general aviation activity across the NAS to determine whether a change observed at an individual airport with LPV procedures is merely reflective of local trends, or it suggests increased throughput enabled by recent LPV implementations. Compared to the nearby non-LPV airports, 58 percent of the airports with LPV approaches and no ILS capabilities experienced higher general aviation traffic growth, as did 46 percent of the airports with both LPV procedures and ILS capabilities. While these outcomes are based on a small number of relevant airports and may not be considerably different from each other, they do confirm higher demand growth at airports with better precision approach capabilities. In the absence of ILS, overall general aviation demand grew at a higher rate at the airports with LPV approaches than it did at the nearby airports without ILS approaches.

References

¹FAA GNSS-GPS WAAS Approaches, http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/approaches/

Required Navigation Performance with Authorization Required Approach Procedures



Area Navigation (RNAV) and Required Navigation Performance (RNP) systems enable point-to-point operations within the coverage of ground- or space-based navigational aids. The two systems provide aircraft with the capability to navigate using performance standards. They are fundamentally similar, with the key difference being a requirement for an on-board performance monitoring and alerting capability that exists only for RNP systems. This requirement improves the precision of navigation through automated monitoring of aircraft performance, and automated alerting of the crew if the required performance is not met.

An RNP system delivers the highest accuracy of navigation, and facilitates a high degree of flexibility in the design of approach procedures. Basic RNP delivers navigation accuracy of 1 nm during the initial, intermediate and missed approach segments, and 0.3 nm on the final approach. Basic RNP approaches can contain Radius-to-Fix (RF) turns, but not on the final approach segment.

RNP with Authorization Required (AR) applies to a specific category of approach procedures that require special aircraft and aircrew authorization similar to Category II/III Instrument Landing System (ILS) operations. Predicated on the aircraft and aircrew requirements, RNP AR approaches allow for reduced lateral obstacle evaluation areas and vertical obstacle clearance surfaces, and may require a capability

to fly an RF turn and/or a missed approach. They deliver navigation accuracy of 0.3 nm during the initial, intermediate and final approach segments, and 1 nm on the missed approach segment. Approval guidance for RNP procedures with AR is elaborated in the FAA's Advisory Circular 90-101A (AC 90-101A).

The FAA has implemented thousands of RNAV and RNP approach procedures over the last decade, with the overwhelming majority being the RNAV (GPS) approaches without RF turns. Each of these implementations was site-specific, and addressed special conditions in its operating environment, including typical weather conditions, airfield configuration, nearby terrain, obstacles, terminal area design and typical traffic flows. Utilization of these procedures varies from site to site, driven by both site-specific issues and performance capabilities of the aircraft typically flying in that environment. Unfortunately, empirical data on procedure utilization is simply not available. However, we can estimate utilization using complex algorithms that consider the extent to which flown trajectories overlap with each published procedure. This method can only be used to estimate utilization of a procedure with a unique design, or a procedure that does not overlap with any of the other nearby procedures.

Because of the importance of addressing site-specific details that may affect procedure utilization, post-operational impact and benefit assessments typically

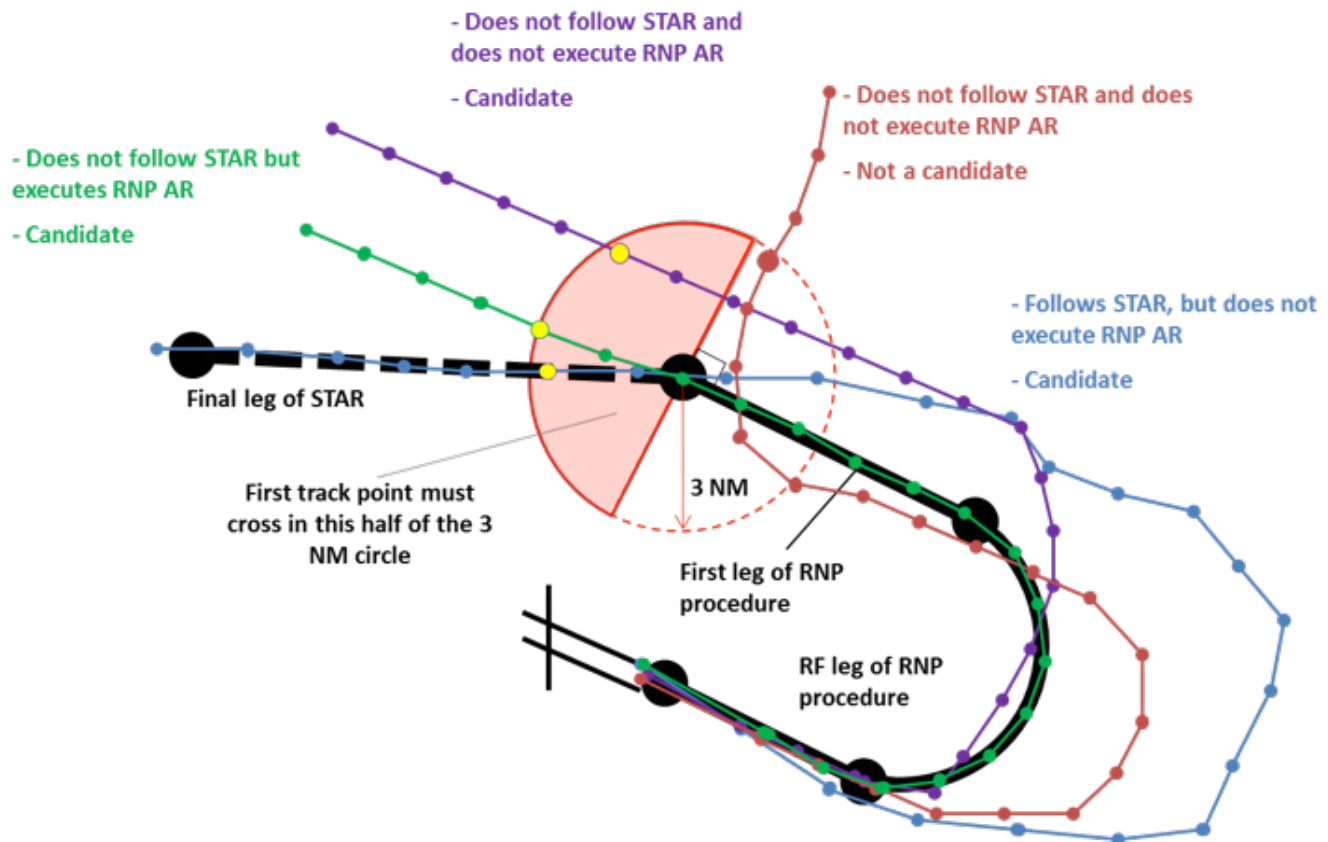


Figure 5 – Requirement for Joining RNP AR Procedure

require a tailored approach. As a result, the FAA has only conducted site-specific assessments up until now. In this document, we describe the first NAS-wide operational impact assessment of RNP approach procedures. Our goal was to facilitate understanding of their overall impacts across the NAS, as well as to gain an understanding of differences in impacts across a wide range of actual implementations and site-specific operational limitations. This was not a traditional post-implementation comparison of performance outcomes observed during periods before and after an implementation, but rather a comparison of performance achieved by different user groups and an assessment of trends observed over two and a half years. To accurately estimate RNP procedure use, we catalogued all of the RNP AR procedures implemented in the NAS through March 2013 and limited our operational impact analysis to only RNP AR approaches with RF turns. The RF turn provides a unique route signature that allows us to differentiate between surrounding traffic and flights that executed the unique route.

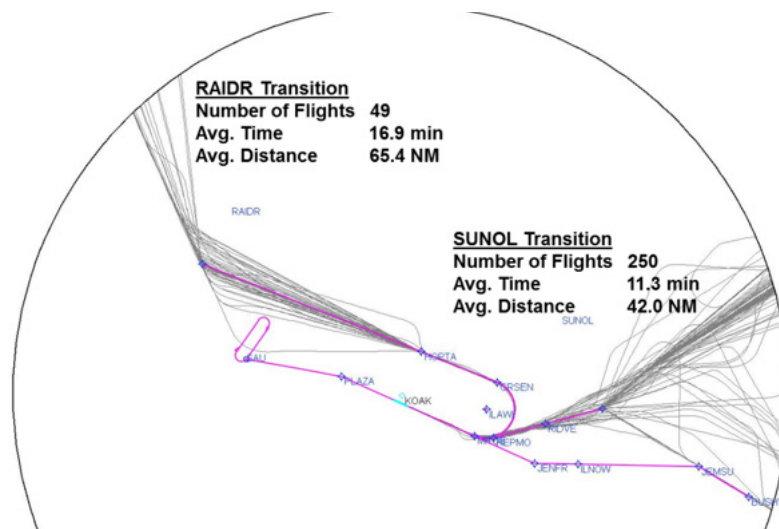
After examining prior RNP studies and procedure specifications, we categorized procedures based on their primary and secondary benefits, including weather minima, noise abatement, airport deconfliction, terrain and obstacle mitigation, vertical guidance, parallel approaches, and defined turn-to-final categories.

We addressed only flight efficiency outcomes and not environmental, system efficiency or airport access. To provide for standardized evaluations across all of the sites and NAS-wide aggregation, we evaluated key performance outcomes using trajectory segments flown within 40 nm of the airport, and compared the outcomes between three key groups of flights:

- Flights that were capable and executed RNP ARs (CE),
- Flights that were capable but did not execute RNP ARs (CNE), and
- Flights that were not capable to fly RNP ARs (NC).

To assign arriving aircraft to the appropriate group, we considered both the direction of flight and the aircraft's navigational capability.

First, we identified flights that could have flown each of the procedures, or the candidate flights. AC 90-101A requires flights to join the last segment before an RF leg at less than 90-degree angle. We also used a 3 nm radius of the waypoints prior to the RF turn to identify candidate flights that were in position to join the RNP AR approach procedure. As illustrated in Fig. 5, the purple, green and blue trajectories represent candidate flights, while the red one does not. Note that a flight can execute



**Figure 6 – OAK RNAV (RNP) Z RWY 29:
RAIDR and SUNOL Transitions**

an RNP AR without first executing a Standard Terminal Arrival (STAR).

Next, focusing only on these candidate flights, we identified their performance capabilities using MITRE's proprietary database of onboard equipment and crew training. If a candidate flight was performed by an airline that had at least one equipped aircraft of the same model and at least one trained aircrew, we assumed the flight was capable of executing an RNP AR approach. All other candidate flights were marked as not capable (NC).

Finally, we identified capable flights that remained within the required lateral threshold after joining the procedure and for longer than 90 percent of the procedure length. The required lateral threshold was equivalent to the RNP value specified for each of the procedure waypoint. We flagged each of these flights as capable and executing the procedure (CE). All other capable flights were marked as capable but not executed (CNE).

In addition, we investigated each procedure's utilization separately for each of its transitions. As an example, consider the approach procedure at Metropolitan Oakland International Airport (OAK), shown in Fig. 6, illustrating the significant differences in distance and time flown by aircraft that execute two different transitions of the same RNAV/RNP approach to runway 29. Compared to the flights on SUNOL transition, aircraft flying the RAIDR transition are about 50 percent longer within 40 nm of OAK. As a result, time and distance savings achieved on the two transitions cannot be directly compared, but need to be separately evaluated and normalized to account for the differences in lateral profiles.

The operational metrics we considered include time, number of level segments, time in level-flight, and time-

weighted altitude. We considered an aircraft to be in level-flight when its altitude remained stable within 200 ft for longer than 50 seconds, and its vertical gradient stayed between 30 ft and 50 ft per nm. Time-weighted altitude is an indicator of vertical flight efficiency that captures both altitudes at which level-offs occur and the duration of each level-off.

We used two key sources of surveillance data, the FAA's Traffic Flow Management System (TFMS) and the National Offload Program (NOP) system, and we evaluated performance outcomes for flights conducted between October 2010 and March 2013. We used the Meteorological Routine Aviation Weather Report (METAR) database to determine operating conditions for each flight, with Visual Meteorological Conditions (VMC) being defined as 5-mile visibility and/or ceilings higher than 3000 ft. Operating conditions that did not meet the VMC criteria were labeled as Non-VMC. All of the outcomes are presented by fiscal year. Note that FY 2013 includes only the period between October 2012 and March 2013.

Operational Performance Assessment

As of March 2013, the FAA has implemented over 4,300 RNAV (GPS) approaches and 359 RNP AR approaches across the NAS. As illustrated in Fig. 7, there were 229 RNP AR approaches with RF turns in the NAS at the end of March 2013, including 172 with a primary benefit mechanism identified as defined turn-to-final. These procedures have published RF turns, often an RF turn of nearly 180 degrees, from the downwind segment to the final approach fix.

The majority of the RNP AR approaches without RF legs aimed to deliver improved vertical guidance or parallel approaches. As illustrated in Fig. 8, there were just a

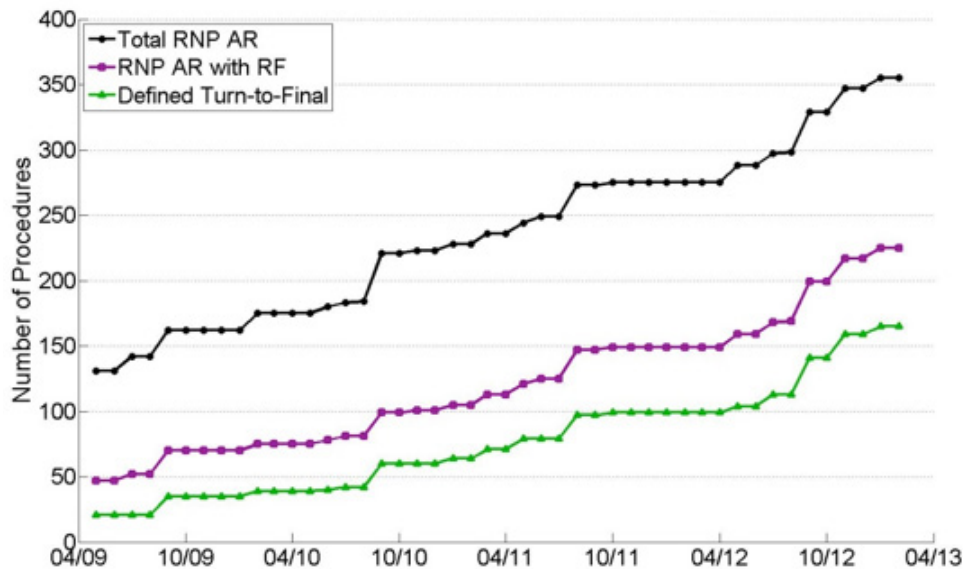


Figure 7 – Number of Available RNP AR Procedures in NAS

few procedures that enabled noise abatement, airport deconfliction or a decrease in weather minima, including procedures at La Guardia, Midway and San Francisco airports.

Close inspection of primary benefit mechanisms of the RNP AR procedures with RF legs revealed that the majority of these procedures enabled a defined turn-to-final, and only 25 percent of all implementations facilitated noise abatement, airport deconfliction, terrain and obstacle mitigation or improvements in vertical guidance. The key secondary benefits mechanism for the procedures with defined turns-to-final were improved vertical guidance and parallel approaches.

The remaining sections present performance outcomes and findings for the 172 RNP AR approaches with defined turns-to-final.

Although increasing with a modest rate over the last few years, utilization of RNP AR approaches with defined turns-to-final remains low across the NAS. As

summarized in Table 6, expressed as a proportion of all flights that land on the active RNP runways, utilization of RNP AR with RF turns barely exceeded 0.5 percent between October 2012 and March 2013, and there were just almost 10 percent of flights capable of executing them.

However, utilization of RNP ARs with RF turns has significantly increased since 2011. As summarized in Table 7, the average number of execution per month tripled between 2011 and March 2013. The increased number of available procedures was the key cause of this significant increase in monthly execution across the NAS. In other words, because of the increased number of RNP AR approaches there will be more candidate flights that land on the runways these approaches lead to, and that arrive from a general direction of the approach transitions. However, compared with 2011, there were a larger proportion of capable flights among candidates in 2013. This outcome, too, appears to have been predominantly driven by the increased number of available procedures across the NAS, and may have

Table 6 – Procedure Utilization by Year and Flight Category

Flight Category	Flights Landing on Active RNP Runways		
	2011 ¹	2012 ²	2013 ³
CE	0.38%	0.34%	0.56%
CNE	5.59%	6.46%	9.57%
NC	18.24%	20.20%	23.58%

¹ October 2010 – September 2011

² October 2011 – September 2012

³ October 2012 – March 2013

Table 7– Procedure Utilization by Year, Operating Conditions and Flight Category

Operating Conditions	Flight Category	Average Number of Monthly Flights			Proportion of Candidate Flights		
		2011	2012	2013	2011	2012	2013
Non-VMC	CE	41	41	123	1.6%	1.1%	1.4%
	CNE	684	952	2,645	26.0%	24.8%	30.9%
	NC	1,904	2,845	5,801	72.4%	74.1%	67.7%
VMC	CE	241	284	643	1.6%	1.3%	1.7%
	CNE	3,455	5,262	10,539	22.6%	23.8%	27.8%
	NC	11,599	16,595	26,675	75.8%	74.9%	70.5%

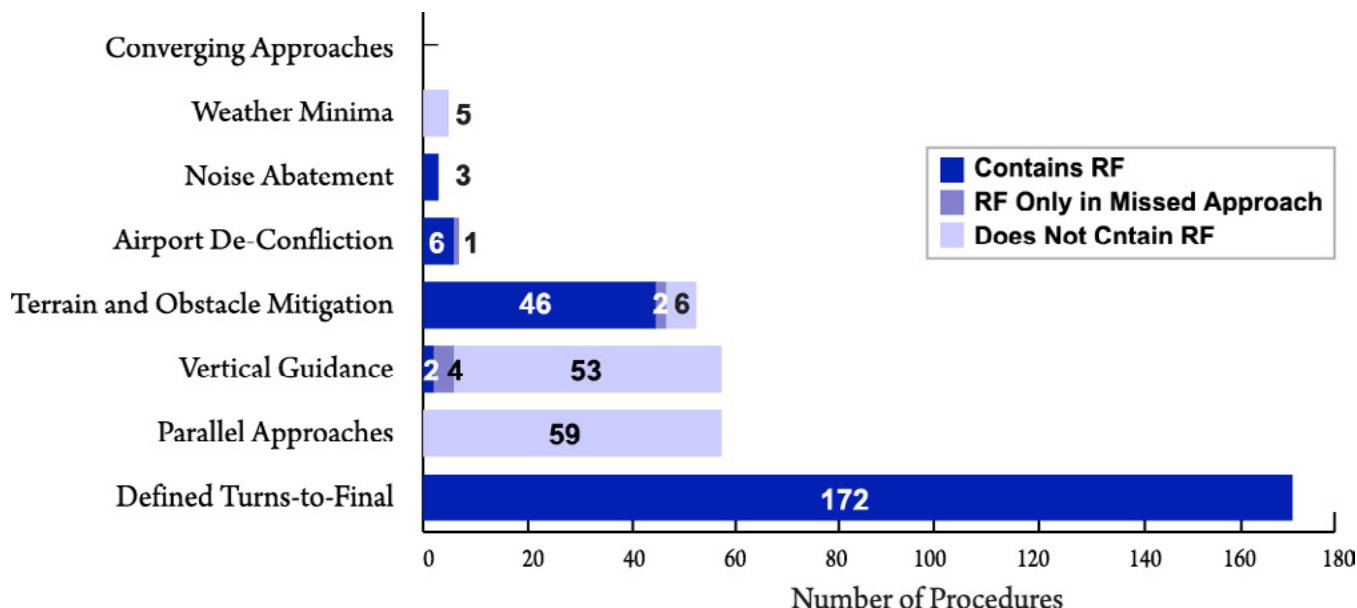


Figure 8 – Procedures by Primary Benefit Mechanism

not been caused by increased operator capabilities or increased use on a per procedure basis. In fact, while we observed an increase in the number of capable candidates (CE and CNE) in FY2013, it was likely a result of both new procedures made available at airports with a high presence of capable operators, and the new procedures designed to complement typical flows and approaches of the capable flights.

In addition, increases in average monthly execution and average monthly candidate flights were of the same magnitude. As a result, expressed as a proportion of candidate flights, utilization of RNP AR approaches with RF turns has been steady since 2011, at about 1.5 percent of candidates irrespective of weather conditions. In other words, a higher proportion of the capable flights chose to not execute the advanced approaches, reaching about 30 percent of the candidates in the first half of fiscal year 2013.

However, aircraft that did utilize RNP AR approaches with RF turns experienced improvements in performance since 2011. As illustrated in Fig. 9, we observed the most

striking improvement in non-VMC conditions, when CE flights experienced 3 percent shorter times, 33 percent fewer level-offs, and 42 percent shorter times in level-flight. In addition, these flights were more predictable too, demonstrated by 10 percent lower standard deviations of time and number of level-offs, and a 40 percent lower standard deviation of time in level-flight.

Aircraft that utilized RNP AR approaches with RF turns also experienced better performance compared to the other two categories of flights. On average, during non-VMC in 2013, CE flights spent 13.1 minutes getting to the runway, had an average of 0.6 level-offs, and spent 1.1 minutes in level-flight within 40 nm of their destination. By comparison, CNE flights were 13 percent longer, experienced more than twice the number of level-offs, and spent three times longer in level-flight. NC flights experienced the worst performance, with almost 24 percent longer times, over three times the number of level-offs and almost five times longer in level-flight.

Comparison of the performance outcomes across different locations throughout the NAS revealed that the most significant flight efficiency benefits from utilizing RNP AR procedures with RF turns are typically realized at locations with no neighboring airports with interacting traffic flows, and no significant terrain or other obstacles that flights have to avoid. In addition, benefits are more likely to be realized at locations with relatively high occurrence of non-VMC and during non-peak times with moderate traffic demand.

In non-VMC, flying an RNP AR procedure with an RF turn resulted in shorter times within 40 nm of the airport across all procedure transitions included in the analysis. In VMC, only about a third of the procedure transitions facilitated time saving when flying these advanced

Table 8 – 2013 Performance Outcomes by Operating Conditions and Flight Category

Weather	Status	Time (minute)	Number of Level-offs	Time in Level-Flight (minute)
Non-VMC	CE	13.1	0.6	1.1
	CNE	14.8	1.5	3.3
	NC	16.2	2.0	5.4
VMC	CE	12.0	0.6	0.9
	CNE	13.0	1.1	2.0
	NC	13.4	1.3	2.9

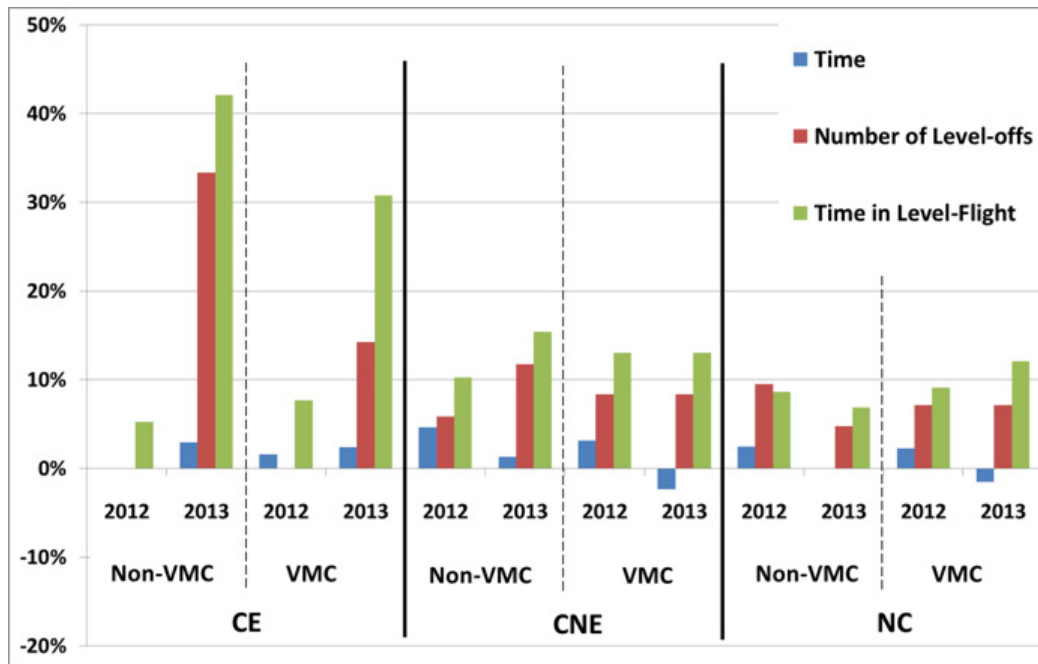


Figure 9 – Changes in Performance Outcomes Relative to 2011

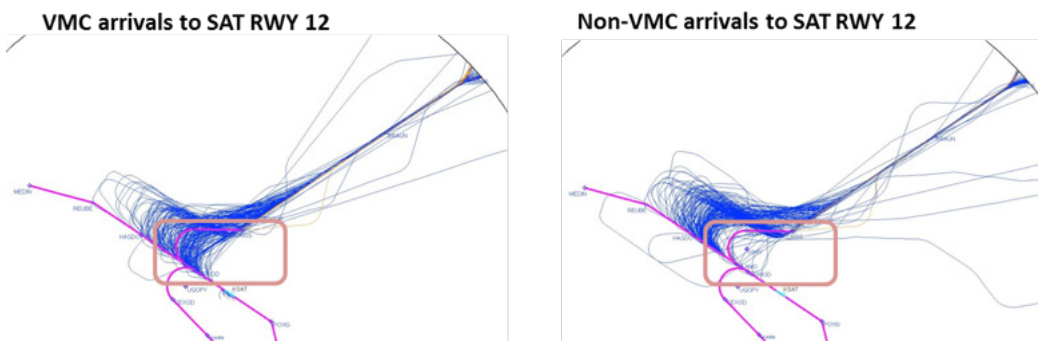


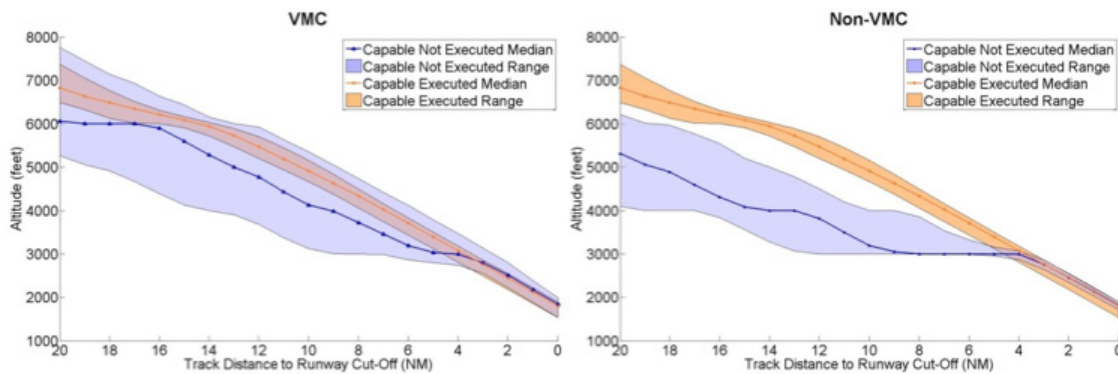
Figure 10 – Differences in Trajectories in VMC and non-VMC: SAT RNP Z 12R, CRISS Transition Shown in Pink

approaches. RNP approaches at Spokane, San Jose, Nashville, Portland and Charleston facilitated the highest times savings relative to the CNE flights.

Aircraft flying RNP AR procedures experienced the largest benefits in terms of lateral and vertical efficiency in non-VMC conditions. As illustrated in Fig. 10, flights often take a longer path on the down-wind segment to intercept the ILS in non-VMC, making the RNP AR procedure a more attractive routing option. However, in VMC, flights often cut corners and fly visual approaches, which can result in significant time saving over any instrument procedure. As illustrated in Fig. 11, the vertical profiles of aircraft executing RNP approaches are more consistent irrespective of weather conditions,

but are usually higher and with fewer level segments in non-VMC. In such cases, the higher the occurrence of VMC, the less opportunity to realize efficiency benefits aircraft may have.

As a result, at some locations, flying an RNP AR approach may result in a less efficient trajectories compared to alternative approach options. Irrespective of the typical weather and other location specific operating conditions, it is important to point out there are additional benefits not addressed in this analysis that can be realized by flying RNP AR procedures, including improved noise profiles, improved predictability, and reduced risks of safety-events.



*Figure 11 – Differences in Vertical Profiles in VMC and non-VMC:
SAT RNP Z 12R, CRISS Transition*

Conclusions

In this document, we describe the first NAS-wide assessment of RNP approach procedures. To provide for an accurate estimate of RNP procedure use, we catalogued all of the RNP AR procedures implemented in the NAS through March 2013, and limited our operational impact analysis to only RNP AR approaches with RF turns. With a goal of facilitating a NAS-wide impact assessment and understanding the differences in impacts across a wide range of actual implementations and site-specific operational limitations, we evaluated and compared performance outcomes between different user groups based on their capability and actual execution of the approaches. We also analyzed performance trends between October 2011 and March 2013.

Comparison of the performance outcomes across different locations throughout the NAS revealed that the most significant benefits from utilizing RNP AR procedures with RF turns are typically realized at locations with no neighboring airports that create interacting traffic flows, and no significant terrain or other obstacles that flights have to avoid. In addition, benefits are more likely to be realized at locations with relatively high occurrence of IMC or Marginal VMC and during non-peak times with moderate traffic demand.

The average monthly use of RNP ARs with RF turns tripled between 2011 and March 2013. In addition, there was a larger proportion of capable flights among candidates in 2013 and a smaller proportion of non-capable flights. The increased number of available procedures was the key cause of these significant increases in monthly execution and proportion of capable flights across the NAS, rather than by increased operator capabilities or increased use on a per procedure basis. Instead, they were likely a result of both new procedures made available at airports with a large number of capable operators, and where the new procedures were designed to complement the typical flows and approaches of capable flights.

Aircraft that utilized RNP AR approaches with RF turns experienced improvements in performance since 2011, with the most striking improvement in non-VMC conditions resulting in 3 percent shorter times, 33 percent fewer level-offs, and 42 percent shorter time in level-flight within 40 nm of their destination. In addition, these flights were more predictable, demonstrated by 10 percent lower standard deviations of time and number of level-offs, and a 40 percent lower standard deviation of time in level-flight.

At some locations, flying an RNP AR approach may result in a less efficient trajectory compared to the alternatives. Overall, however, aircraft that utilized RNP AR approaches with RF turns experienced the best flight efficiency and predictability. During non-VMC in 2013, flights were 13 percent shorter within 40 nm of their destination, experienced half as many level-offs, and spent 70 percent less time in level-flight compared with the capable flights that did not execute the approaches. Compared with the non-capable flights, they were almost 24 percent shorter, even less likely to level-off, and spent 80 percent less time in level-flight.

Irrespective of the typical weather and other location specific operating conditions, it is important to point out there are additional benefits from flying RNP AR procedures not addressed in this analysis, including improved noise profiles, improved predictability, and reduced risks of safety-events. In collaboration with MITRE CAASD, the FAA will extend this analysis to address safety benefits and estimate monetary benefits resulting from differences in performance discussed in this report, including savings in direct operating costs and passenger value of time for the aircraft using the advanced procedures.

End-to-End Performance Based Navigation



The FAA is implementing advanced Performance Based Navigation (PBN) procedures to enable aircraft with required performance capabilities to fly more consistent and direct routes. PBN defines air traffic performance requirements in terms of operational capabilities of aircraft and represents a shift from conventional, ground-based navigation aids and procedures to satellite-based navigation aids and area navigation procedures. It improves navigational precision and provides more efficient and flexible routing options.

The two main components of PBN are Area Navigation (RNAV) and Required Navigation Performance (RNP). RNAV utilizes GPS and enables point-to-point operations, while RNP also includes an onboard monitoring and alerting capability that delivers even higher navigational accuracy. In addition to the existing conventional procedures, flights that are capable of performing to the required standard can use RNAV Standard Instrument Departure (SID), RNAV Standard Terminal Arrival Route (STAR), and RNAV or RNP Instrument Approach Procedures (IAP). These RNAV and RNP procedures have been implemented throughout the National Airspace System (NAS) to facilitate terminal area operations and transitions to and from en route airspace. In the en route airspace, in addition to the existing V- and J-Routes, the same flights can also use RNAV T-Routes when flying below 18,000 ft and RNAV Q-routes when flying along or above 18,000 ft and up to 45,000 ft.

RNAV and RNP procedures and routes have been traditionally implemented to facilitate traffic flows by focusing on the needs and requirements of individual terminal areas and en route airspace segments. PBN routes are expected to provide benefits to both NAS users and service providers. For service providers, the use of PBN should reduce controller workload by de-conflicting flows, and minimize the need for vectoring and communications between pilots and controllers. For NAS users, these routes are expected to provide more predictable trajectories that could also result in improved efficiency through a reduction in delay, flight time and fuel burn.

In many regions throughout the NAS, aircraft can now fly end-to-end (E2E) PBN routes that connect en route with terminal and approach procedures for full PBN connectivity. However, the actual utilization of E2E PBN routing depends on the extent to which it may facilitate efficient operations. The most efficient routing is sometimes equivalent to the most direct routing, while in other cases terrain, winds and weather may contribute to a longer route being more efficient for the operators. As a result, if more efficient, operators may resort to “cutting corners” as they transition from one PBN procedure to another rather than following all of the procedures perfectly. Other important issues that influence the utilization of procedures are aircraft performance capabilities, including airframe performance limitations, onboard equipment and crew training.

Clearly, E2E PBN utilization depends on the actual operating conditions between the origin and destination airports. Unlike the available routing options which are static, operating conditions and the actual utilization of PBN procedures change daily. This study examines operational performance outcomes of flights between a select set of airport pairs where E2E PBN connectivity is available, and focuses on flight efficiency and predictability as a function of the extent to which PBN procedures are utilized.

The corridor between the Pacific Northwest, and California and Phoenix was among the first regions in the NAS with an E2E PBN routing option. Q-Routes were implemented in 2003 connecting Portland International Airport (PDX), Seattle-Tacoma International Airport (SEA) and Vancouver International Airport (CYVR) with San Francisco International Airport (SFO), Metropolitan Oakland International Airport (OAK) and San Jose International Airport (SJC) in the Northern California, and Phoenix International Airport (PHX) in Arizona.

Table 9 – E2E RNAV Routes for the Select Airport Pairs

Airport Pair	RNAV SID	Q-Route	RNAV STAR	RNP AR
SEA-OAK	HAROB4	Q5	RAIDR2	R11/R29
PDX-PHX	WHAMY2	Q35	MAIER5	N/A
	CASCD1	Q13		

The recent amendments or additions of SIDs at SEA and PDX, and STARs at OAK and PHX enabled E2E connectivity between SEA and OAK, and PDX and PHX. In Table 9, we identify routing options that provide E2E PBN connectivity between the two airport pairs.

The most direct Q-routes available between PDX and PHX, Q35 and Q13, are designed to circumvent the restricted areas surrounding the Nevada Test and Training Range. As illustrated in Fig. 14, even though not fully connected from origin to destination, Q-Routes Q5, Q7 and Q11 provide alternate routing options.

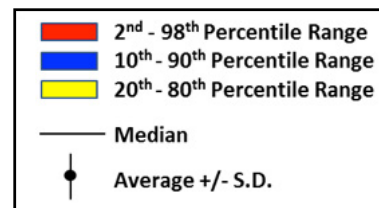
There are three key incentives for operators to use advanced PBN routing: increased consistency of flown trajectories resulting in improved predictability, improved routing resulting in improved efficiency or reduced environmental impacts, and improved flow management resulting in increased access. Between the airport pairs included in this analysis, each of the three incentives may contribute to alleviating the congestion around busy airports. The corresponding benefits may be realized through shorter and more predictable times, including reduced delays, as well as through less frequent use of MIT restrictions to manage arrival flows. The new STARs are also designed to provide more continuous

descent paths for arrivals into these airports. Therefore, we expect traffic using the routes to fly shorter distances and times in level-flight due to improved vertical profiles. In comparison with flights using the alternative jet routes, aircraft flying the E2E PBN routes are expected to achieve more efficient and predictable performance.

Operational Performance Assessment

To study the performance impacts of E2E PBN utilization, we evaluated and compared performance outcomes for the following four key categories: Full E2E PBN, Partial E2E PBN, No E2E PBN and No PBN. We assumed that a flight executed Full E2E PBN if its trajectory conformed to the underlying PBN procedures from take-off through landing, with some minor corner cutting allowed for smoother transitioning from one PBN procedure to the next. If a flight followed PBN procedures from origin to destination but executed more extensive corner cutting that resulted in only partial conformance to each of the underlying procedures, we assumed that it executed a Partial E2E PBN route. Finally, we used the No E2E PBN category to capture flights that followed only some of the available PBN procedures but not in a fully connected manner from origin to destination, and the No PBN category to capture flights whose trajectories did not conform to any of the available PBN procedures.

For this analysis, if a trajectory conformed to at least 80 percent of a given procedure segment laterally within the prescribed threshold, it was assumed that the flight had flown that segment. We used a lateral threshold of 1 nautical mile (nm) for RNAV SID, RNAV STAR and Q-route, 0.5 nm for RNAV IAP, and 0.3 nm for RNP Authorization Required (AR).



We used one year of surveillance data, between October 2011 and September 2012, to compare performance of flights based on the extent to which they conformed to the available PBN procedures. Detailed performance analysis for each of the airport pairs is presented in subsequent subsections below, and the legend above applies to all charts summarizing flight efficiency outcomes.

SEA-OAK

In FY12, there were 10 to 15 daily flights between SEA and OAK. As illustrated in Fig. 12, E2E connectivity is provided by the HAROB4 RNAV SID at SEA, route Q5, and a portion of the RAIDR2 RNAV STAR that extends into the Runway 11/29 RNP AR with an RF leg at OAK. The Q5 route is 8 miles shorter than the alternative jet route between the two airports and represents the most

direct en route routing option. The portion of the STAR that aircraft use to transition from the Q-route to the RNP procedure is comprised of a single segment that is common with the RNP procedure and represents a minor share of the E2E PBN routing for this airport pair. As shown in Table 10, flights between SEA and OAK utilize RNAV SID and route Q5 to a higher extent than STAR.

Table 10 – SEA-OAK: Conformance to PBN Procedures

Procedure Type	Conformance
SID	98.0%
Q	84.4%
STAR	28.5%
IAP (RNP RF)	1.4%

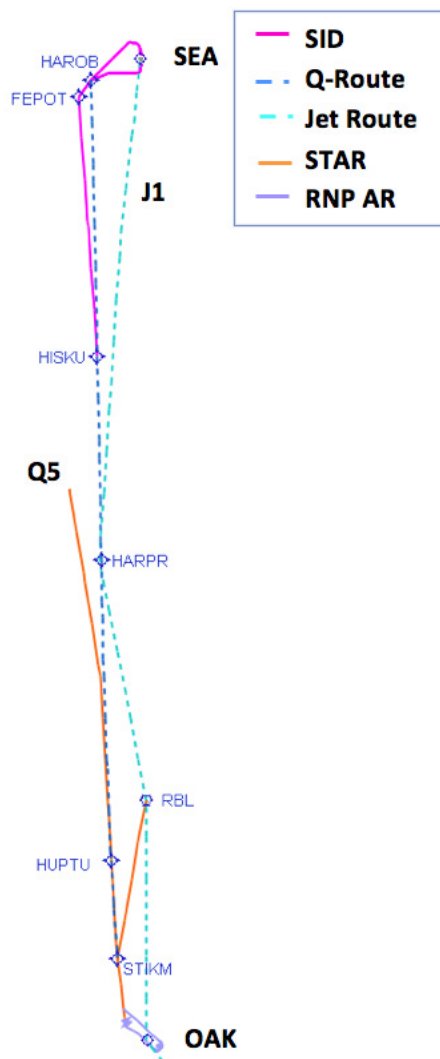


Figure 12 – SEA-OAK PBN Routes

Less than 1 percent of flights between SEA and OAK typically conform to the full E2E PBN trajectory that includes RNP AR with RF leg at OAK, and about 8.5 percent conform to the connected underlying RNAV SID, Q-Route and STAR procedures. In addition, less than 1 percent of flights flew No PBN procedures at all, and almost all of these flights were on a Bombardier Dash 8 Q400 (coded as DH8D in the Traffic Flow Management System) aircraft type, which due to its service ceiling limitations, does not typically fly altitudes reserved for Q-Routes. We did not observe significant differences in procedure utilization during peak periods as the use of E2E PBN did not vary with traffic levels.

Flights flying full E2E PBN experienced the best performance. Despite flying longer airborne distances, these aircraft flew shorter and more predictable times and experienced shorter delays.

Due to insignificant variation in end-to-end connectivity along the available PBN procedures, flights that conformed to Full E2E PBN procedures experienced little variance in their airborne distances. In fact, the coefficient of variance for airborne distance was below 0.7 percent for these flights, and up to 3.8 times higher for the flights in the other three categories.

The most striking difference in airborne distance and time was between the Full E2E PBN and the No PBN aircraft. Full E2E PBN aircraft flew 27 nm or 4.5 percent longer distance, but 24 minutes or 28.5 percent shorter times on average. Because almost all the No PBN aircraft were Bombardier Dash 8 Q400, this difference in flight efficiency is attributable to aircraft performance characteristics rather than routing preferences. Airborne distance of the Full E2E flights was within 1 percent of the Partial E2E and No E2E flights, while airborne times were almost 4 and 7 percent shorter, respectively.

Interestingly, the variances in distance and time for the aircraft that did not use any PBN procedures were lower than those flights using partial and no E2E PBN procedures. These outcomes were driven by the fact that almost all the flights that did not fly PBN procedures were conducted on the same aircraft type. As a result, they experienced lower variance in the flown trajectories.

In addition to the shortest airborne times and most predictable trajectories, Full E2E PBN flights also accumulated the shortest delays. In fact, compared to the other three categories, block delay of Full E2E PBN flights was up to 5.7 minutes shorter on average, and its variance between 10 and 15 times smaller.

We found no difference in performance outcomes between the four categories in the departure phase of

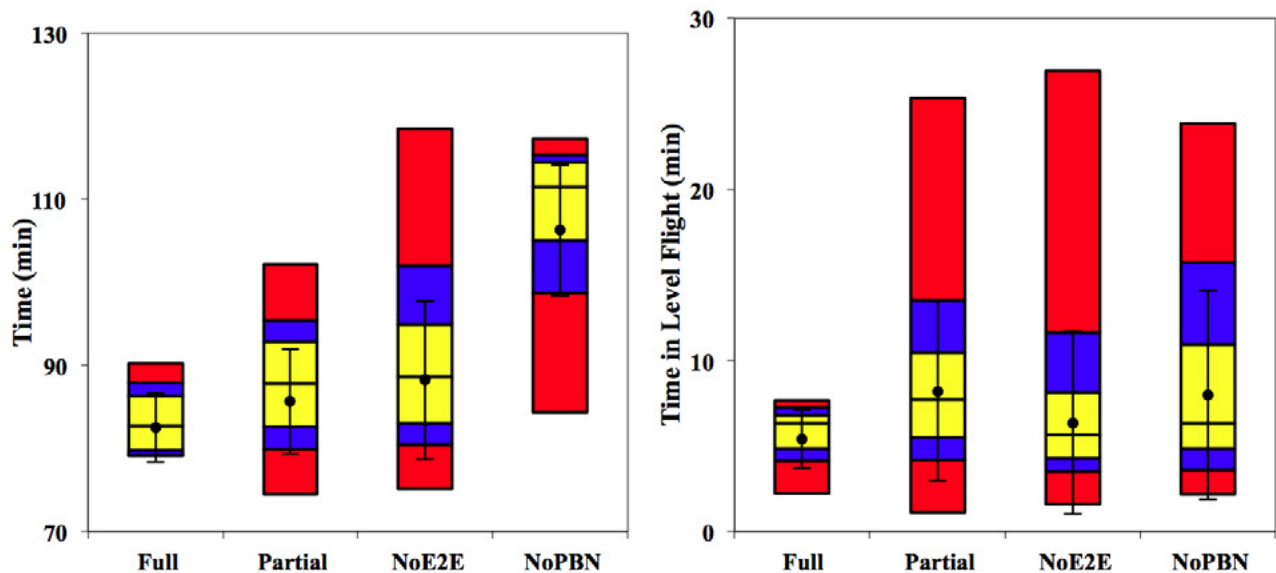


Figure 13 – SEA-OAK: Flight Efficiency Outcomes

the flight. In the arrival phase however, Full E2E PBN flights experienced about one level-off fewer than other flights on average, and spent up to 2.8 minutes shorter in level-flight below top of descent.

PDX-PHX

On average, there are between 10 and 12 daily, direct flights between PDX and PHX. There are two E2E PBN routing options for the flights between these two airports, via Q13 and Q35. These two Q-Routes, designed to circumvent the restricted areas surrounding the Nevada Test and Training Range, represent the most direct Q-Routes available for this airport pair. As illustrated in Fig. 14, there are other Q-Routes available from PDX to PHX but they are not directly connected to the RNAV SIDs and STARs.

Table 11 – PDX-PHX: Conformance to PBN Procedures

Procedure Type	Conformance
SID	50.9%
Q	47.3%
STAR	98.3%

As summarized in Table 11, less than 1 percent of flights from PDX to PHX do not follow available PBN procedures.

Less than 1 percent execute Full E2E, 23 percent execute Partial E2E, and 75 percent execute only individual PBN procedures.

Note that even though an RNP AR approach into PHX is available, it is not in our analysis because we estimate the utilization outcomes by considering conformance of the flown trajectories to the published procedures. This RNP AR is a straight-in approach that is undistinguishable from the overlaying approaches, including the ILS.

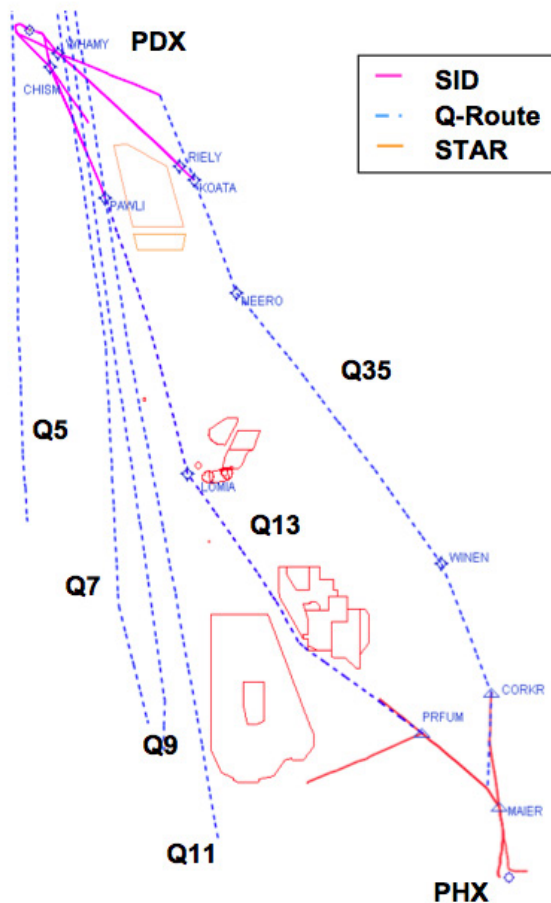


Figure 14 – PDX-PHX: E2E PBN Routing Options

Aircraft that executed Full E2E PBN were the most

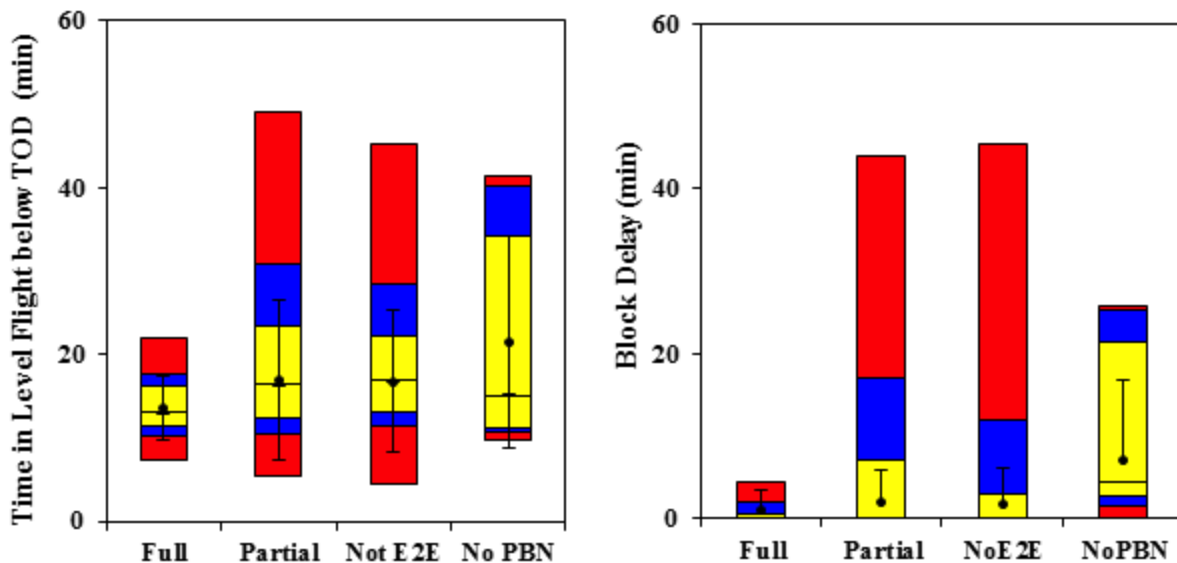


Figure 15 – PDX-PHX Performance Outcomes

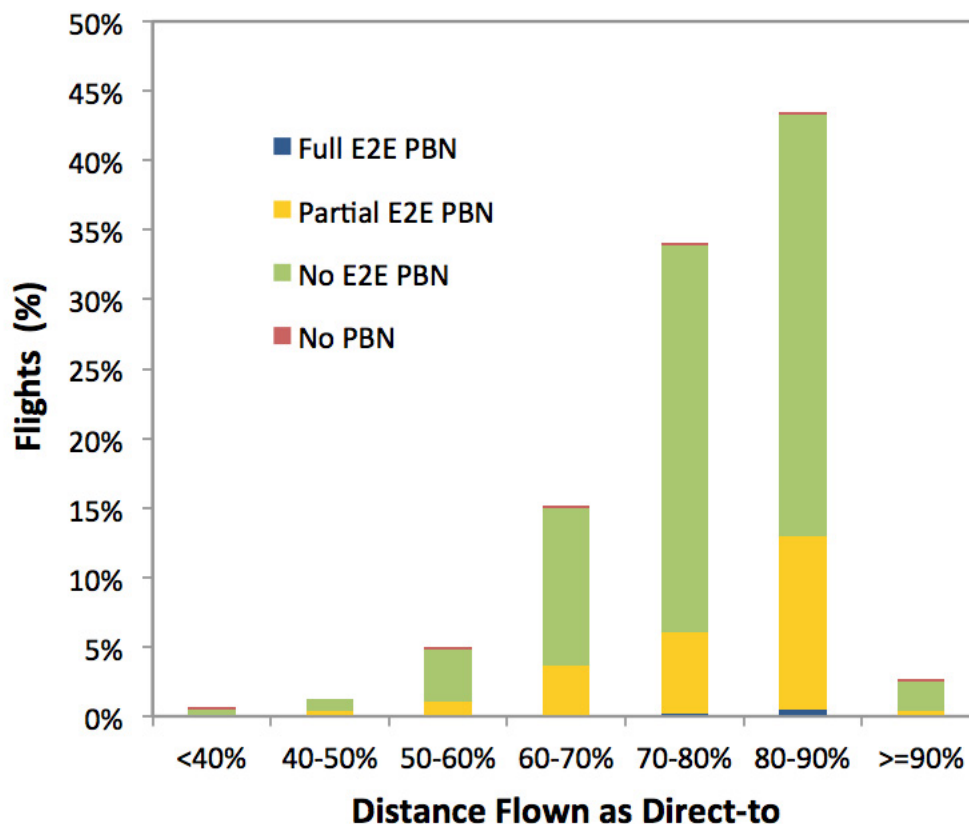


Figure 16 – Distribution of Flights by Distance Flown Directly from a Waypoint to a Waypoint

efficient due to the shortest airborne distance and time flown on average, and the most predictable due to the smallest variances in these outcomes. As illustrated in Fig. 13, these aircraft flew 917 nm and 131 minutes on average, with a standard deviation within 0.5 and 5.7 percent of the average values, respectively. Aircraft that executed Partial E2E PBN routing and No E2E PBN routing were close behind, about 1 percent longer on average. Compared to the Full E2E PBN aircraft, we observed up to five times higher standard deviation of distance flown by these aircraft with no significant

difference in variability of time. On the other hand, aircraft that flew No PBN procedures proved to be both less efficient and less predictable. They flew 3 percent longer distance and 6 percent longer time on average, with standard deviation of distance and time 14 times and three times higher, respectively, than those of Full E2E PBN aircraft.

In addition, as illustrated in Fig. 15, the Full E2E PBN flights experienced the shortest block and arrival delays, both under a minute on average. Block and arrival delays

were on average about 1.5 and 2.5 percent higher for the Partial E2E PBN and No E2E PBN flights and about 5.8 and 4.6 percent times higher for the No PBN flights.

A more detailed analysis revealed that Full E2E PBN routing was predominantly used during times of peak demand between 1800 and 2400 Greenwich Mean Time, when aircraft that flew Full E2E PBN routing continued to experience the shortest distances and times, and aircraft that flew Partial and No E2E PBN routing remained within 1 percent on average.

On the other hand, the difference in performance between these aircraft and aircraft that flew No PBN procedures widened during peak times. Compared with Full E2E PBN aircraft, No PBN aircraft flew 51 nm and 19 minutes longer during peak times, or a difference of 6 and 15 percent, respectively. In addition, aircraft in this group also experienced the highest variance in airborne distance and time, with their standard deviations of 66 nm and 35 minutes, or about 14 times and 3 times higher than those of the Full E2E PBN aircraft, respectively.

In addition, aircraft that flew Full E2E achieved shorter block and arrivals delay during peak times, about 6 minutes and 7 minutes lower than No PBN on average. These flights were also the most predictable as the variances of their performance outcomes were the lowest across the four PBN categories.

Clearly, flights between PDX and PHX utilized available PBN procedures, but typically not in a fully connected manner from origin to destination. To circumvent the restricted airspace, these aircraft exercised flexibility in using different routing options, resulting in distances up to 6 percent longer than the shortest distance between the two airports. In fact, about 80 percent of aircraft flew directly from a waypoint to a waypoint for over 70 percent of their distance rather than along a published route.

The remaining analysis investigated the impact of such point-to-point routing on flight efficiency. Because filed routes were the only insight into operator preferences, we were not able to assess flexibility directly. We focused on the trade-off between flexibility and efficiency instead.

To determine the extent to which an aircraft flew directly from one waypoint to another, referred to as distance flown as direct-to, we first identified the fixes and waypoints it flew through on its way from PDX to PHX. Then, we studied the segments between consecutive waypoints and assumed the aircraft flew direct-to if the distance flown along the segment falls within 10 percent of the Great Circle Distance (GCD) between the starting and ending waypoints. Finally, we aggregated these segment-level considerations, and determined the proportion of overall distance flown direct-to as the ratio between the distance flown along these segments and the overall distance. Fig. 16 illustrates distribution of flights by distance flown directly from one waypoint to another between PDX and PHX.

To facilitate understanding differences in performance outcomes depending on the extent to which aircraft fly point-to-point, we considered the following four categories:

1. Aircraft with less than 70 percent of distance flown as direct-to,
2. Aircraft with 70 to 90 percent of distance flown as direct-to,
3. Aircraft with more than 90 percent of distance flown as direct-to, and
4. Full E2E PBN.

It is important to point out that imperfect data caused us to relax our criteria for PBN procedure conformance evaluation to allow for corner cutting. Previously, operators transitioned from SID to Q-Route by bypassing the last portion of the SID and the first portion of the Q-Route due to inefficient connectivity between RNAV procedures at PDX in the original procedure specifications. As a result, all of the Full E2E PBN flights fall within the category of aircraft with distance flown as direct-to between 70 and 90 percent. Interestingly, only 2.5 percent of aircraft flew directly from a waypoint to a waypoint for more than 90 percent of the overall distance between origin and destination, and most of them executed some PBN procedures but not in a fully connected manner from PDX to PHX.

Table 12 – Summary of Flight Efficiency Outcomes by Category of Point-to-Point Operations

Distance Flown as Direct-to	Number of Flights ¹	Distance ²		Time (min)		Avg. Planned Distance ³ (nm)
		Avg.	S.D.	Avg.	S.D.	
< 70%	778 (21.5%)	935.58	28.32	133.30	9.12	927.75
70% – 90%	2,753 (76%)	922.89	15.11	131.50	7.08	919.62
>= 90%	92 (2.5%)	916.57	11.89	130.92	6.23	919.50
Full E2E PBN	26 (0.7%)	916.06	4.11	130.94	7.35	923.03

¹ Total number of flights: 3,623

² GCD distance: 878 nm

³ Based on filed flight plans

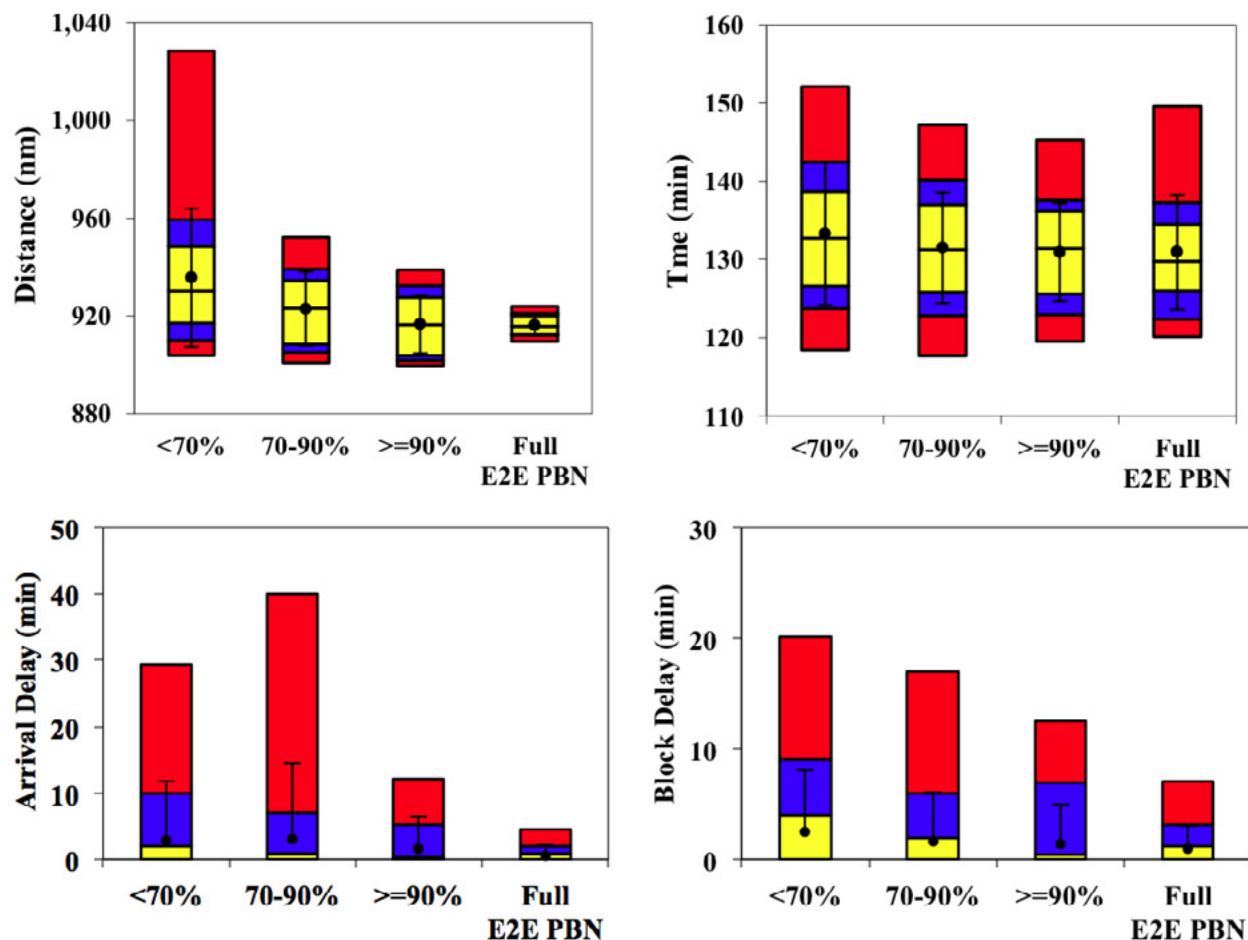


Figure 17 – Flight Efficiency Outcomes by Category of Point-to-Point Operations

Table 12 summarizes key performance outcomes for the four categories of point-to-point operations, indicating a greater difference in variance of distance between the four categories than in variance of time. The same observation is better depicted in Fig. 17, which shows that the range of observed distances varies more between the four categories than does the range of observed times. This finding implies that operators use different routing options to manage their flight times more effectively.

Even though the difference in time between the four categories is insignificant, Fig. 17 indicates the advantage of flying point-to-point by pointing out that the more an aircraft flies directly from a waypoint to a waypoint, the shorter its time and delay are overall. In fact, compared to aircraft that flew less than 70 percent of its distance as direct-to, aircraft that flew at least 90 percent of its distance as direct-to flew 16 nm and 3 minutes shorter and experienced 3 minutes lower block delay and 4 minutes lower arrival delay. Full E2E PBN aircraft flew between 70 and 90 percent of the distance between PDX and PHX directly from a waypoint to a waypoint, and experienced the most efficient and the most predictable trajectories, including the lowest delays.

Conclusions

The corridor between the Pacific Northwest, and California and Phoenix was among the first regions in the NAS with an E2E PBN routing option. While Q-Routes have been available since 2003 in this region, the recent addition or amendment of RNAV SIDs and STARs allow for better connection with the Q-Routes. As a result, flights can now utilize E2E PBN routing options the entire way from origin to destination airports.

In this analysis, we assessed differences in performance between flights from SEA to OAK and from PDX to PHX based on the extent to which they utilize E2E PBN routing. We categorized flights into four categories: Full E2E PBN, Partial E2E PBN, No E2E PBN and No PBN, and compared their performance outcomes.

Overall, less than 1 percent of flights from SEA to OAK and from PDX to PHX utilized full E2E PBN routing. However, compared to the flights in the other three categories, these flights experienced the best performance, as they proved to be the most efficient and predictable. While they did not always fly the shortest distance, they experienced the shortest flight times and lowest arrival delays, as well as shortest time in level-

flight and least level-offs below Top of Descent.

Due to the lower variance in their trajectories, aircraft flying fully connected PBN procedures from origin to destination were incorporated with less frequent and less penalizing traffic management initiatives. As a result, we can infer that E2E PBN routing facilitated merging and spacing of these flights into the arrival airport flows.

The SEA to OAK E2E PBN route presents the most direct route between that airport pair. The Q-Route connecting the two airports is shorter than the existing jet route by 8 nm. Full E2E PBN flights experienced overall better efficiency and predictability compared to all other categories of flights. Airborne distance of Full E2E flights was within 1 percent of that of Partial E2E and No E2E flights, while airborne times were almost 4 and 7 percent shorter, respectively. We observed a greater difference in airborne distance and time between Full E2E PBN and No PBN aircraft. However, because almost all the No PBN aircraft were Bombardier Dash 8, this difference in flight efficiency is attributable to aircraft performance characteristics rather than routing preferences.

Block delay for Full E2E flights was up to 5.7 minutes shorter on average than that of other flights, and its variance between 10 and 15 times smaller. In the arrival phase, Full E2E PBN flights experienced about one level-off fewer than other flights on average, and spent up to 2.8 minutes shorter in level-flight below top of descent.

Flights from PDX to PHX have to circumvent several special use airspace areas, including the restricted areas surrounding the Nevada Test and Training Range. Operators can choose from several E2E PBN routing options between these two airports, with the E2E routes including Q13 and Q35 being the shortest. Our analysis found that the majority of flights filed these E2E PBN routes, however less than 1 percent actually

flew Full E2E PBN routes. Again, Full E2E PBN flights experienced the best overall performance, including efficiency and predictability. In comparison, No PBN aircraft flew 3 percent longer distance and 6 percent longer time on average, while during peak times this difference in distance and time further widened to 6 and 15 percent, respectively.

A closer inspection of 99 percent of the flights between PDX and PHX that did not fly full E2E PBN routes revealed that these flights were likely capitalizing on the key aspects of satellite-based navigation that enables point-to-point navigation between any two waypoints for equipped operators. Our analysis indicates that the more an aircraft flies directly from a waypoint to a waypoint, the shorter its time and delay are overall. In fact, compared to aircraft that flew less than 70 percent of its distance as direct-to between consecutive waypoints, aircraft that flew at least 90 percent of its distance as direct-to flew 16 nm and 3 minutes shorter and experienced 3 minutes lower block delay and 4 minutes lower arrival delay. Despite the different routing choices and higher variability in flown distances, we observed similar variances in flight times across all flights. This observation indicates that operators use different routing options to manage their flight times more effectively.

It is important to point out that these conclusions may not be possible to extrapolate to other airport pairs with E2E PBN connectivity. The two airport pairs are unique in that the Q-Routes have been in use for a number of years and operators have had a chance to adjust their usual operating practices. Other important issues that influence utilization of PBN procedures include performance capabilities of aircraft typically flown between an airport pair, including airframe performance limitations, onboard equipment and crew training.

Optimized Profile Descent Procedures at Reagan National and Dulles International Airports



Under the auspices of the Washington D.C. Optimization of Airspace and Procedures in the Metroplex effort, Optimized Profile Descent (OPD) RNAV STARs were implemented at Ronald Reagan Washington National Airport (DCA) and Washington Dulles International Airport (IAD) on August 6, 2012. As illustrated in Fig. 18, two new OPD Area Navigation (RNAV) Standard Terminal Arrivals (STARs), FRDMM1 and TRUPS1, replaced the ELDEE5 RNAV STAR into DCA, and a new OPD RNAV STAR, GIBBZ1, replaced the SHNON2 RNAV STAR into IAD. OPDs are designed to reduce fuel consumption and noise by maintaining a constant

and optimal descent angle during landing. In addition to reducing level-offs in terminal airspace, the FRDMM1, TRUPS1, and GIBBZ1 STARs provide shorter paths into the two airports for arrivals from the west.

As illustrated in Fig. 19, the new STARs also separate DCA and IAD arrivals from the west to provide the lateral separation necessary to accommodate more efficient descents to both airports. The lateral shift to the north on the FRDMM1 STAR eases the integration of DCA and IAD departure traffic and allows for unrestricted climb profiles into the en route airspace. The lateral shift to

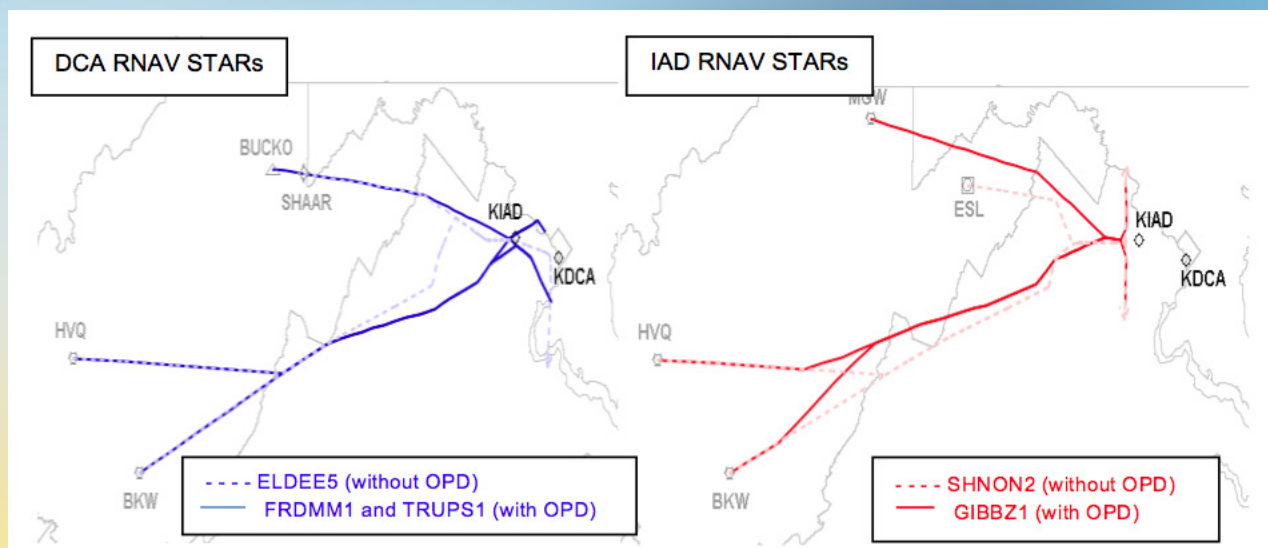


Figure 18 – DCA and IAD: Lateral Profiles of RNAV STARs

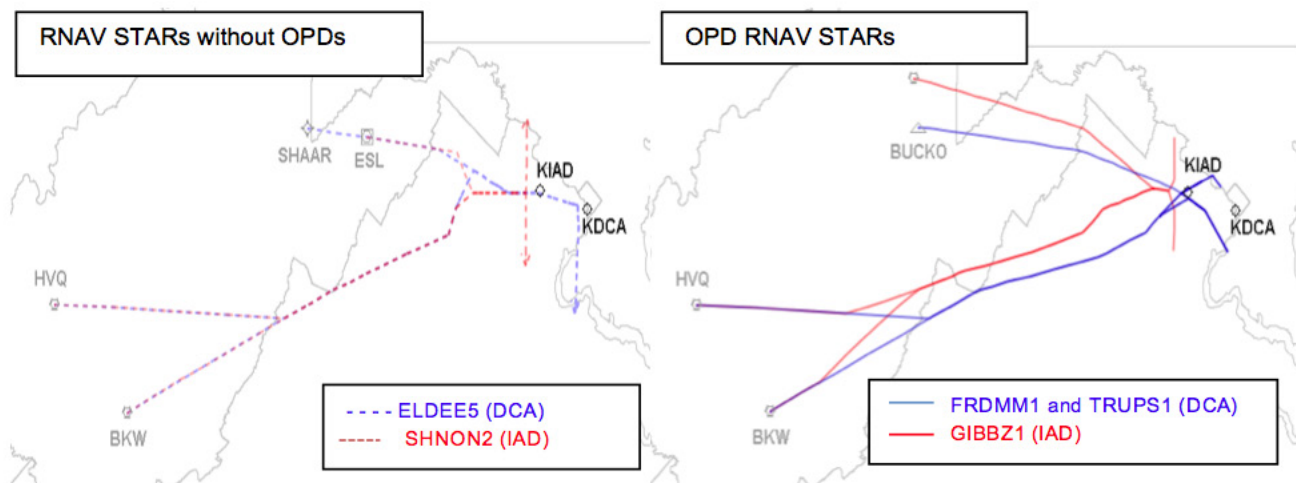


Figure 19 – DCA and IAD: DCA and IAD: Lateral Interactions between STARs

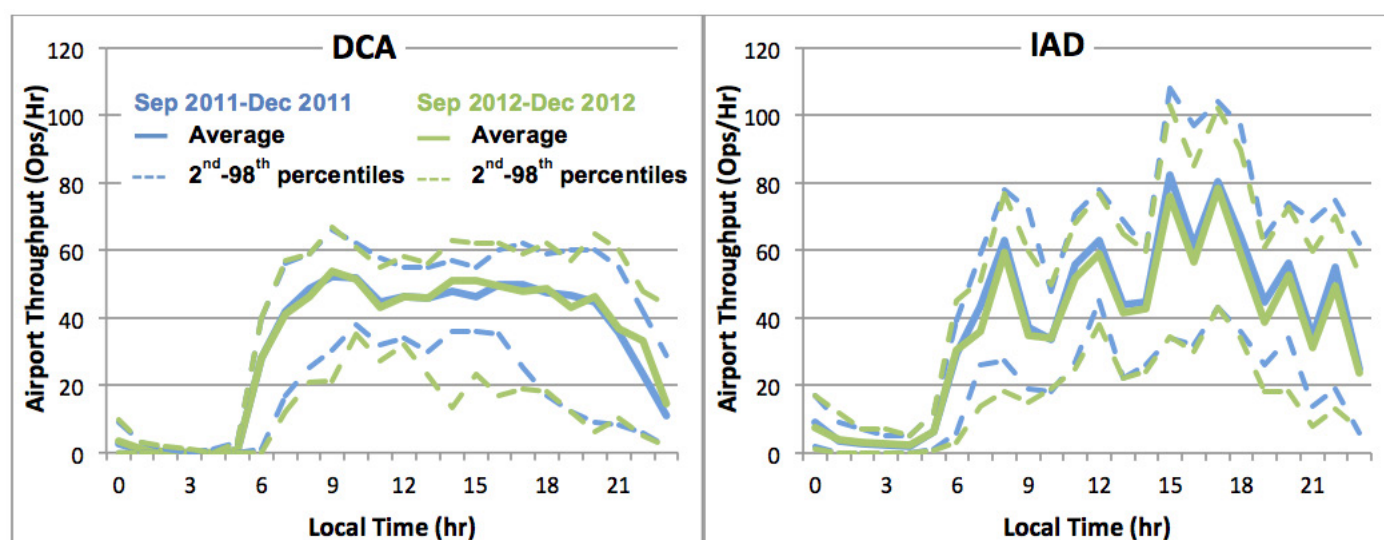


Figure 20 – Distribution of Average Hourly Operations

the southeast on the TRUPS1 STAR provides additional airspace for sequencing westbound departure traffic from DCA and IAD. The lateral shift to the north on both the northwest and southwest legs of the GIBBZ1 STAR keeps DCA and IAD arrival traffic sufficiently separated on the new OPD STARs.

Because the new routes are more direct with less interaction, we expect to see a decrease in distance and time typically spent in the en route and terminal areas. Furthermore, the improved vertical profiles of the OPDs should result in a substantial decrease in distance and time in level-flight.

To assess the impact of the OPD RNAV STARs, we analyzed operational performance outcomes by investigating the changes in 4D trajectories before and after the implementation of the STARs. We selected September 2011 to December 2011 as the pre-implementation period of interest and September 2012 to December 2012 as the post-implementation period

of interest. We focused on jet aircraft operations, as the OPD RNAV STARs are for jets only, within a 250-nautical mile (nm) range of DCA and IAD. Flights that originated and ended within the 250-nm range of the two airports were not included in the analysis. We evaluated flight distance and time as indicators of lateral efficiency, as well as distance and time in level-flight as indicators of vertical efficiency. We further analyzed performance outcomes by weather and conformance. Weather was categorized by Visual Meteorological Conditions (VMC) and Instrument Meteorological Conditions (IMC) as defined by 14 CFR Part 91 weather minima. We assumed that a flight was conforming to a procedure when it flew within 1 nm laterally of the procedure for more than 80 percent of the length of the procedure.

Operational Performance Assessment

Compared to the analogous period before implementation of RNAV STARs with OPDs, total operations at DCA increased 1.3 percent during the 4 months analyzed

Table 13 – DCA and IAD: Total Operation Counts and Conformance to STARs

Time Period	DCA		IAD	
	Total Operations	Conformance to West STARs	Total Operations	Conformance to West STARs
September 2011 — December 2011	94,252	32%	117,642	14%
September 2012 — December 2012	95,506	78%	109,236	52%

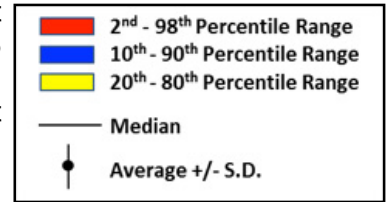
following implementation, while those at IAD decreased 7.1 percent. As illustrated in Fig. 20, the decrease in overall demand at IAD has not caused a significant change in the characteristics of demand. Peak periods are still occurring at the same time of day and are of a similar magnitude as they were in the past. In addition, hourly demand profile remained the same as well.

As summarized in Table 13, utilization of the west RNAV STARs increased at both airports after OPD implementation, from 32 to 78 percent at DCA, and from 14 to 52 percent at IAD. The change in procedure utilization during IMC was somewhat higher in IMC at DCA, from 44 to 85 percent, and at IAD, from 16 to 49 percent. Although demand and weather have not changed significantly at either airport, aircraft are flying along a greater portion of the STARs, suggesting that the increase in conformance to the STARs is not the result of change in demand or weather but of the implementation of the new OPD RNAV STARs. An increase in conformance means that aircraft are executing more consistent and predictable trajectories, which are likely to result in reduced controller/pilot communications and flow interactions, as well as increased accuracy of airline fuel planning.

DCA Performance Impacts

As illustrated in Fig. 21, across all DCA arrivals from the west distance and time within 250 nm of the airport decreased by 2.0 nm and 0.51 minutes per flight on

average after OPD RNAV STARs implementation. We observed increased consistency of flown trajectories, with standard deviations of distance and time decreasing from 21.7 nm to 17.7 nm and 6.0 minutes to 5.0 minutes, respectively. However, as illustrated in Fig. 4, DCA arrivals realized the most significant improvement during IMC when distance and time decreased 7.9 nm and 2.3 minutes per flight on average, or 3 and 5 percent, respectively. The legend on the right applies to Fig. 21 through Fig. 24.



One of the most significant benefits of the new OPD RNAV STARs lies in improved vertical efficiency. As illustrated in Fig. 22, for DCA arrivals from the west, distance and time in level-flight below Top of Descent (TOD) decreased 13.9 nm and 2.4 minutes per flight on average, and up to 14.1 nm and 3.2 minutes, respectively. Again, DCA arrivals realized the most significant improvement during IMC when distance and time in level-flight below TOD were reduced by 18.0 nm and 3.4 minutes per flight on average, or 30 and 28 percent, respectively.

IAD Performance Impacts

IAD arrivals from the west experienced similar operational performance improvements. As illustrated in Fig. 23, across all IAD arrivals from the west, distance

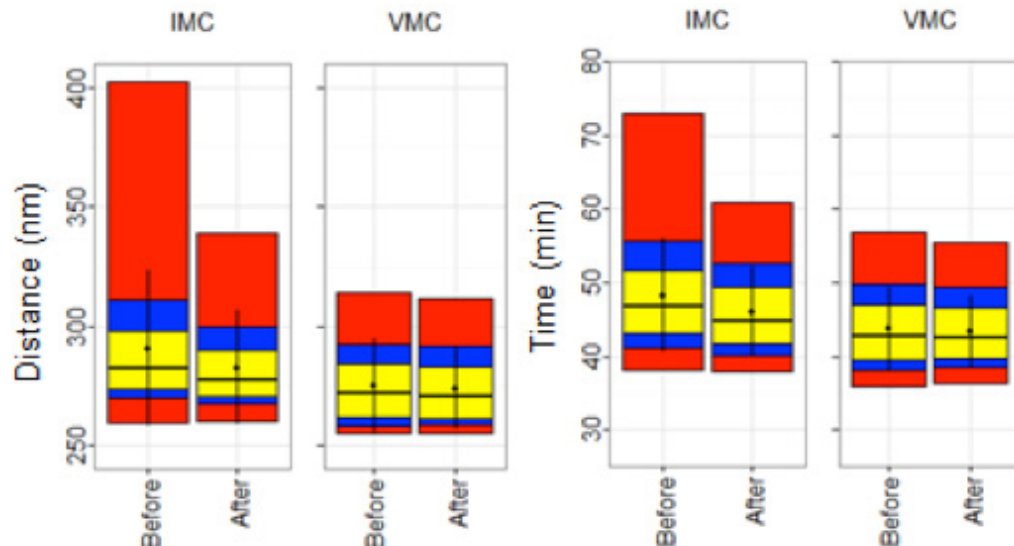


Figure 21 – DCA: Lateral Efficiency Outcomes for West Arrivals

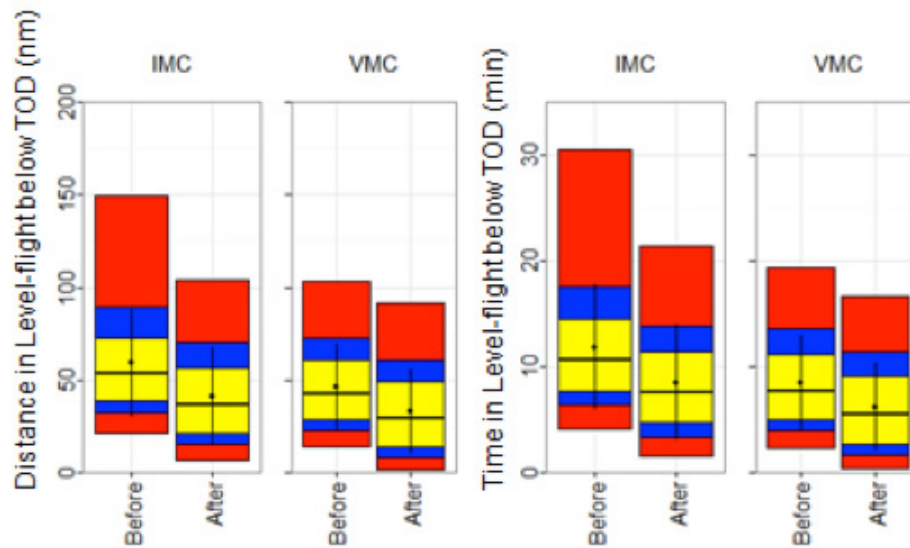


Figure 22 – DCA: Vertical Efficiency Outcomes for West Arrivals

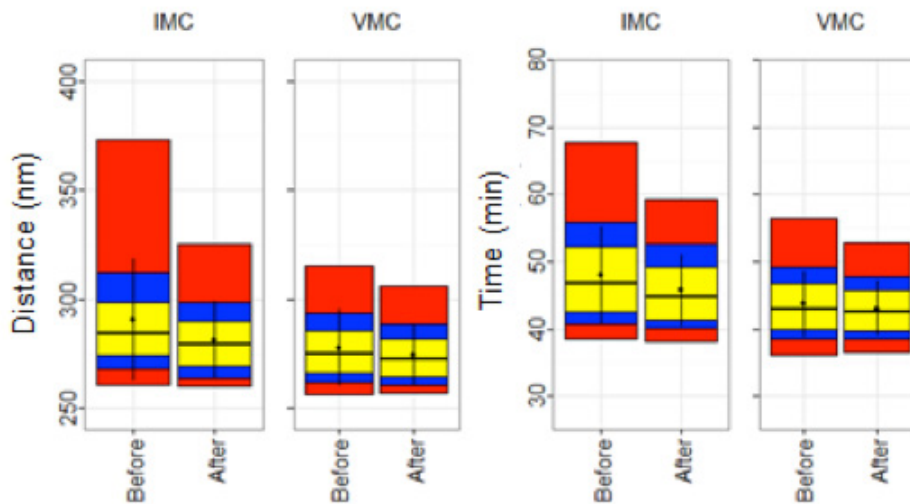


Figure 23 – IAD: Lateral Efficiency Outcomes for West Arrivals

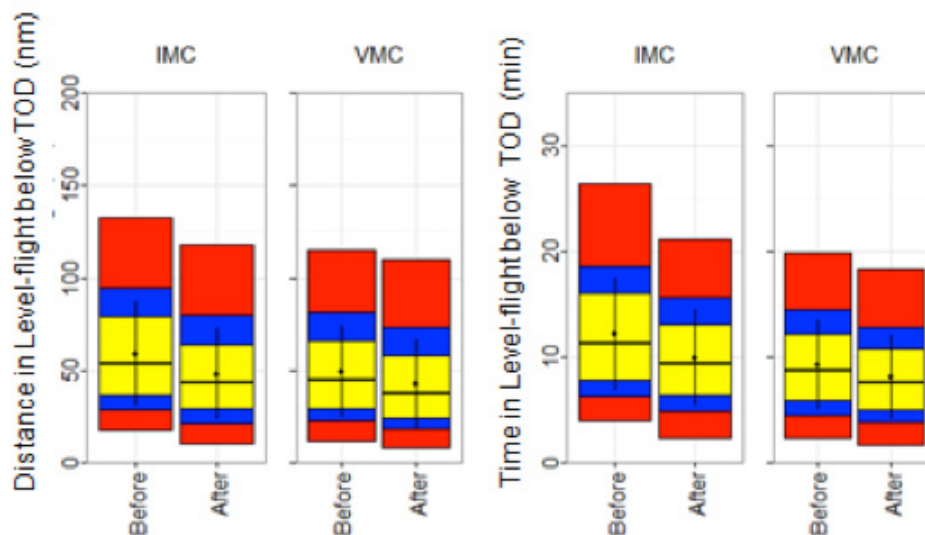


Figure 24 – IAD: Vertical Efficiency Outcomes for West Arrivals

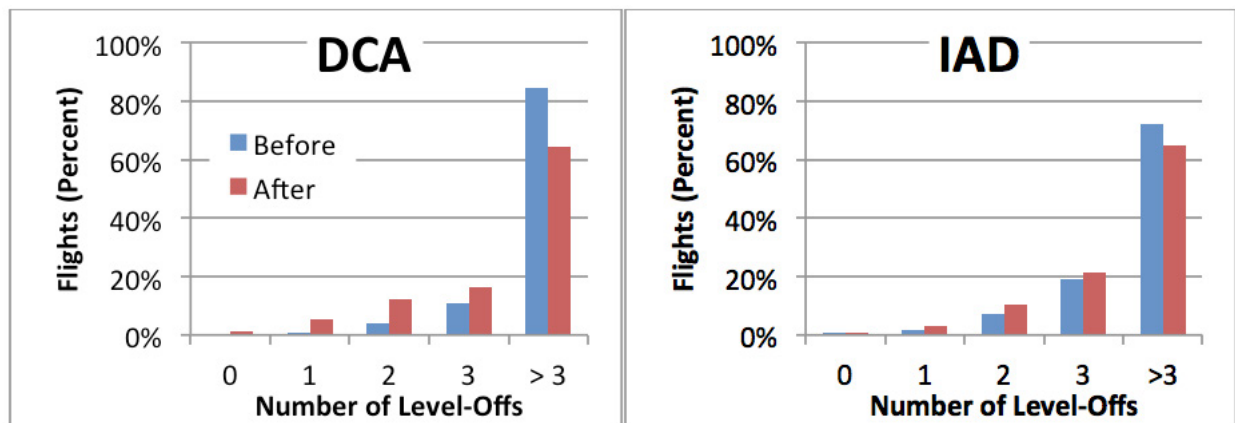


Figure 25 – DCA and IAD: Distribution of Level-offs per Flight

and time within 250 nm of the airport decreased 4.1 nm and 0.95 minutes per flight on average, and up to 15.3 nm and 4.7 minutes, respectively. Again, as with the DCA arrivals, we observed a significant improvement in consistency of the actual 4D trajectories, with standard deviation of distance and time decreasing from 19.4 nm to 14.8 nm and from 5.4 minutes to 4.3 minutes, respectively. Once again, the most significant reduction occurred during IMC, when distance and time within 250 nm of the airport decreased 8.9 nm and 2.3 minutes per flight on average, or 3 and 5 percent, respectively.

We observed improvement in vertical profiles flown by IAD arrivals from the west, with distance and time in level-flight decreasing 7.4 nm and 1.3 minutes. As shown in Fig. 24, the benefits are even higher in IMC, with improvement in distance and time in level-flight reaching 11.0 nm and 2.2 minutes, or 19 and 18 percent, respectively.

Level-off Impacts

After the implementation of the new OPD RNAV STARs, the number of level-offs that flights experience during their descent decreased 18 percent for DCA arrivals and 4 percent for IAD arrivals. As illustrated in Fig. 25, the change in distribution of level-offs indicates a higher proportion of flights experiencing up to three level-offs. In addition, the chart shows a 20 percent decrease in flights that experience more than three level-offs for DCA arrivals and a 7 percent decrease for IAD arrivals.

Conclusions

Under the auspices of the Washington Metroplex effort, the FAA introduced three new OPD RNAV STARs at DCA and IAD in August 2012.

The procedures, designed to reduce fuel consumption and noise by maintaining a constant and optimal descent angle during landing, provide shorter routes for arrivals from the west to both airports and facilitate more efficient vertical profiles. In addition, the new STARs also separate DCA and IAD arrival flows, enabling fewer interactions.

Post-implementation analysis of the resulting impacts indicate improved lateral and vertical efficiencies, more consistent flight distances and times and greater conformance to the procedures. There was a decrease in average flight distance and time across all flights, as well as duration in level-flight, with the most significant improvements realized during IMC.

The most significant improvements were realized during IMC, when distance and time flown within 250 nm of DCA and IAD decreased 3 and 5 percent, respectively. Distance and time in level-flight below TOD decreased 30 and 28 percent, respectively, at DCA, and 19 and 18 percent, respectively, at IAD.

Finally, the number of level-offs during descent over all conditions decreased 18 percent for DCA arrivals and 4 percent for IAD arrivals. In addition, we observed a 20 percent decrease in flights that experience more than three level-offs for DCA arrivals, and a 7 percent decrease for IAD arrivals.

Optimized Profile Descent Procedures at Memphis International Airport



The FAA implemented four new Optimized Profile Descent (OPD) Area Navigation (RNAV) Standard Terminal Arrivals (STARs), FNCHR1, LTOWN6, TAMMY4, and MASHH1, at Memphis International Airport (MEM) on July 26, 2012. As illustrated in Fig. 26, the new procedures are primarily overlays of existing conventional STARs with improved vertical profiles. No altitude restrictions existed on the procedures prior to implementation. The OPD RNAV STARs contain altitude

windows designed to provide for a constant and optimal descent angle during landing.

As the lateral profiles of the procedures were not changed significantly, improvements in lateral efficiency are not expected. However, the improved vertical profiles of the OPDs should result in a substantial decrease in distance and time in level-flight.

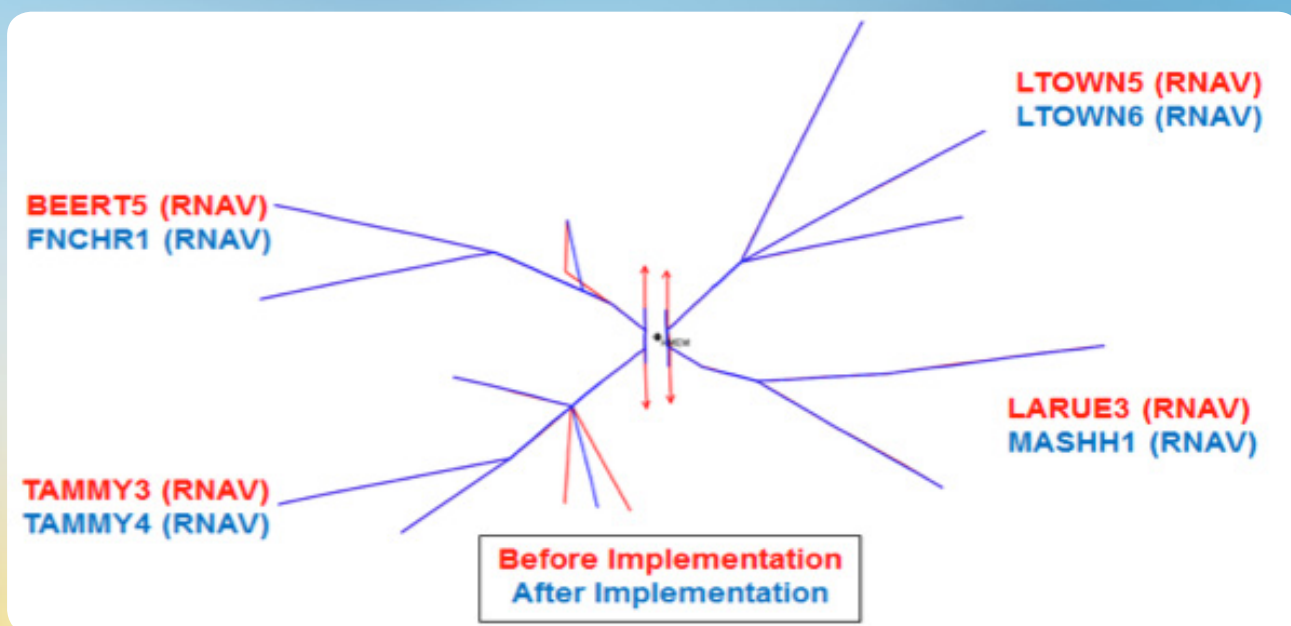


Figure 26 – MEM: Lateral Profiles of RNAV STARs before and after OPD Implementation

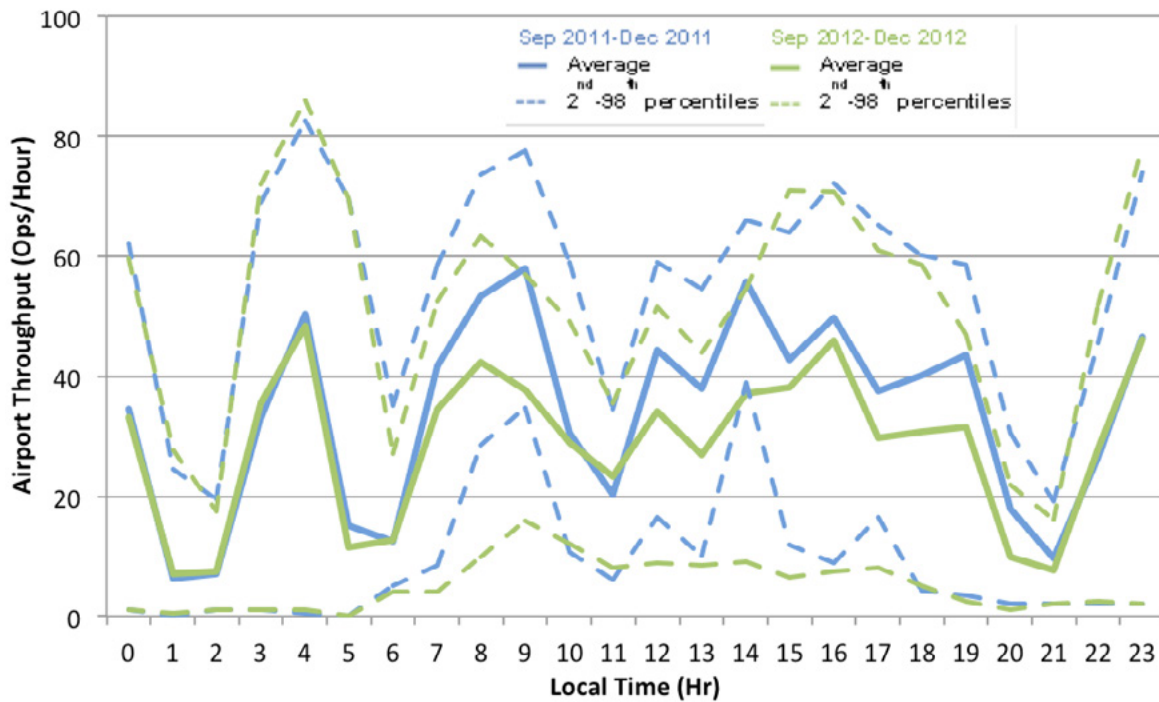
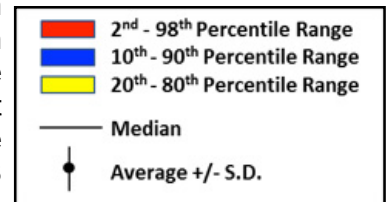


Figure 27 – MEM: Distribution of Average Hourly Operations

To assess the impact of the OPD RNAV STARs, we analyzed operational performance outcomes by investigating the changes in 4D trajectories before and after the implementation of the STARs. We selected September 2011 to December 2011 as the pre-implementation period, and September 2012 to December 2012 as the post-implementation period. On November 1, 2012, we implemented Wake Turbulence Recategorization Separation Standards (RECAT) at MEM. To differentiate between the impacts of the two implementations, we further segregated the data into periods from September through October when only OPD RNAV STARs were available, and November through December when both the new procedures and the RECAT were available. We focused on jet aircraft operations within a 250 nm range of MEM since the OPD RNAV STARs are for jets only and the OPD STARs are fully encompassed by that range. Flights that originated and ended within the 250 nm range of the two airports were not included in the analysis.

We evaluated flight distance and time as indicators of lateral efficiency, and distance and time in level-

flight as indicators of vertical efficiency. We analyzed performance outcomes by weather and conformance. Using the 14 CFR Part 91 weather minima specifications, we identified the occurrences of VMC and IMC at MEM. Finally, we assumed that a flight was conforming to a procedure when it flew within 1 nm laterally of the procedure for more than 80 percent of the length of the procedure. The legend on the right applies to the range charts included in Fig. 28 and Fig. 29.



Operational Performance Assessment

Compared to the analogous period before recent implementations, overall demand at MEM decreased 14.5 percent. However, as illustrated in Fig. 27, most of that decrease occurred during the day, while peak night operations remained as intense as they were in the past. The occurrence of IMC during the last 4 months in 2012 remained at the same level as in 2011.

As summarized in Table 14, after implementation of the OPDs, utilization of the RNAV STARs increased at MEM, from 16 to approximately 39 percent before RECAT implementation, and to 38 percent after RECAT. Under IMC, utilization of the RNAV STARs increased from 12 to 39 percent after implementation of the OPD STARs but before RECAT, and from 21 to 40 percent after implementation of both OPD STARs and RECAT. An increase in procedure utilization means that

Table 14 – MEM: Total Operations Counts and Conformance to STARs

Time Period	Total Operations	Conformance to STARs
September — October 2011	99,906	16%
November — December 2011		16%
September — October 2012	84,932	39%
November — December 2012		38%

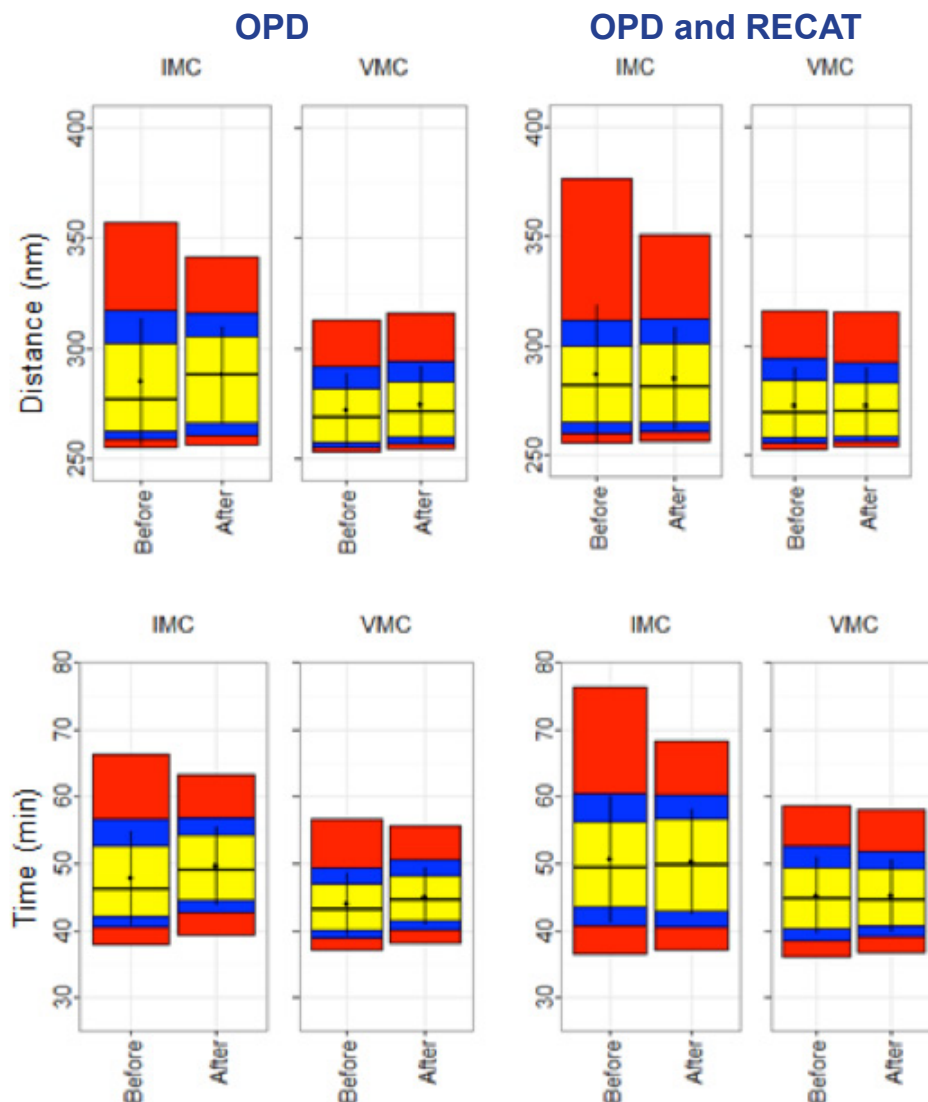


Figure 28 – MEM: Lateral Efficiency Outcomes for Arrivals

aircraft are executing more consistent and predictable trajectories, further resulting in reduced controller and pilot communications and potential interactions, and increasing accuracy of fuel planning for airlines.

As illustrated in Fig. 28, distance and time within 250 nm of the airport increased 2.8 nm and 1.2 minutes per flight on average after the implementation of the OPD STARs and before implementation of RECAT. However, after the introduction of the new RECAT criteria, the distance and time decreased 0.6 nm and 0.21 minutes on average. In IMC, distance and time increased 3.2 nm and 1.8 minutes per flight on average before RECAT, and 1.6 nm and 0.3 minutes per flight on average after RECAT.

We observed increases in flown distance and time caused by increased conformance to the RNAV STARs and decreased corner cutting. However, this initial negative impact was alleviated by more efficient flows after RECAT implementation. In fact, improved efficiency of arrival flow management further resulted in a significant decrease in negative impacts of holding

that controllers typically use to maintain safety of arriving aircraft as they merge and space them on their final descent to MEM. Compared to the analogous period from the year before, we observed a 3.9 percent increase in holding events but a 3 percent decrease in average holding duration during the first 2 months after OPD implementation. After RECAT, occurrence of holding events decreased 55.6 percent and average duration of holding decreased almost 10 percent, which resulted in a 49 percent reduction in total minutes in holding.

Another, even more significant benefit of the recent implementations lies in improved vertical efficiency. As illustrated in Fig. 29, during the first 2 months after the OPD RNAV STAR implementation, distance and time in level-flight decreased 5.0 nm and 0.83 minutes on average, or 15 and 13 percent, respectively. After introduction of the new RECAT criteria, the same performance outcomes continued to decrease for a total reduction of 21 and 23 percent, respectively, in VMC and 26 percent in IMC.

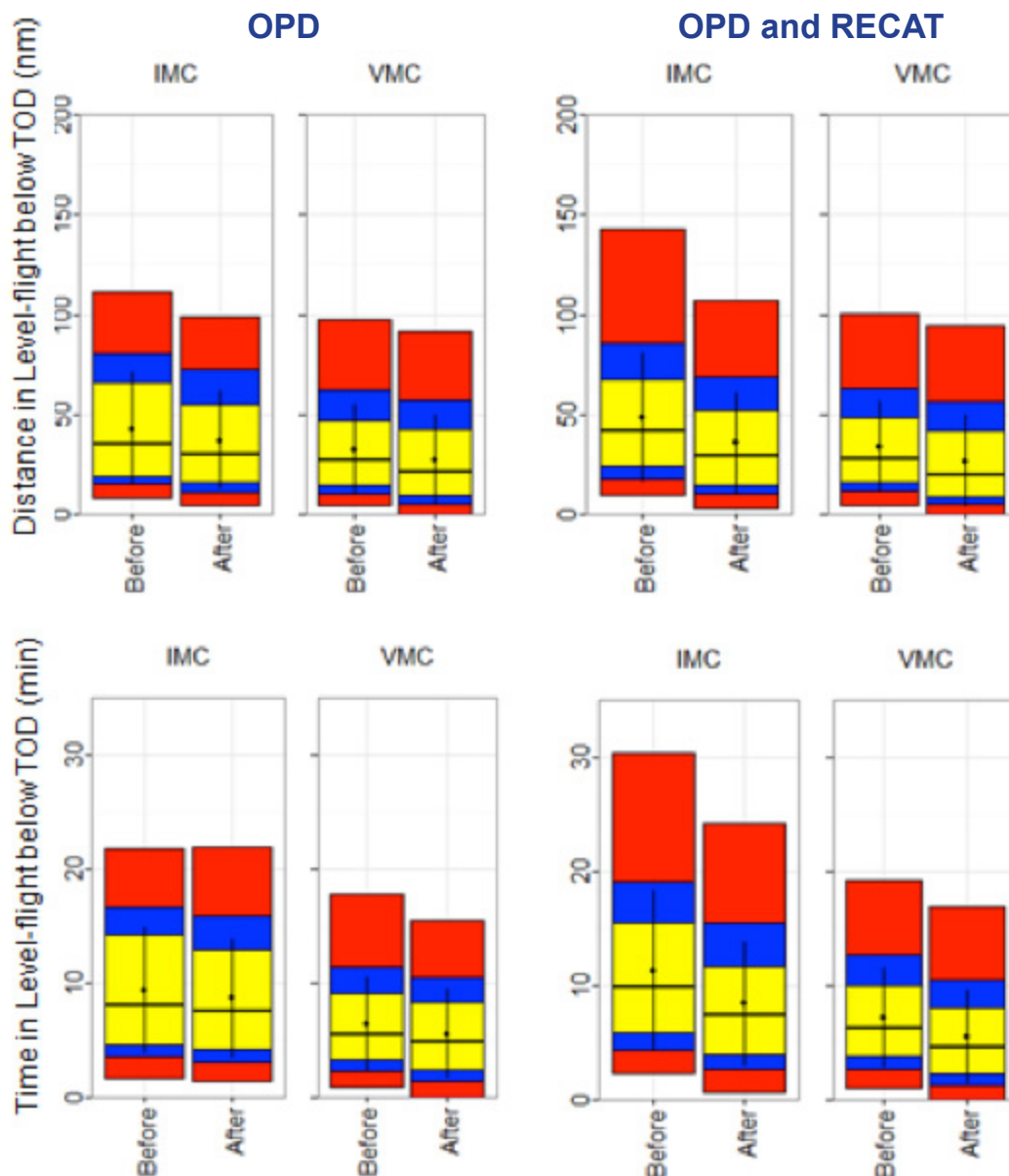


Figure 29 – MEM: Vertical Efficiency Outcomes for Arrivals

As illustrated in Fig. 30, we observed an increase of about 2.5 percent in arrivals without level-offs after recent implementations. Average number of level-offs per flight was reduced 12 percent during the first 2 months after implementation of the OPD STARs, and 17 percent during the 2 months after RECAT. The most significant contributor to this improvement was a reduction in flights that experienced more than three level-offs with a 10 percent reduction after OPD implementation, and an almost 17 percent reduction after RECAT.

Conclusions

In July 2012, the FAA implemented four new OPD RNAV STARs at MEM. Designed as overlays of existing conventional STARs, the new procedures did not aim to improve lateral flight efficiency. However, their design improves vertical profiles and enables an

increase in vertical flight efficiency. In November 2012, we implemented new RECAT separation standards, enabling additional flight efficiency improvements.

After implementation of OPDs, utilization of the RNAV STARs increased from 16 to almost 40 percent. The new procedures were utilized to the same extent in both VMC and IMC. Initially, increased conformance to the RNAV STARs caused decreased corner-cutting and, thus, increased distance and time flown within 250 nm of MEM. However, this negative impact was alleviated by more efficient flows after RECAT, when we observed a decrease in distance and time of 0.6 nm and 0.21 minutes on average.

More significantly, improved efficiency of arrival flow management enabled by RECAT further resulted in a significant decrease in holding that controllers typically

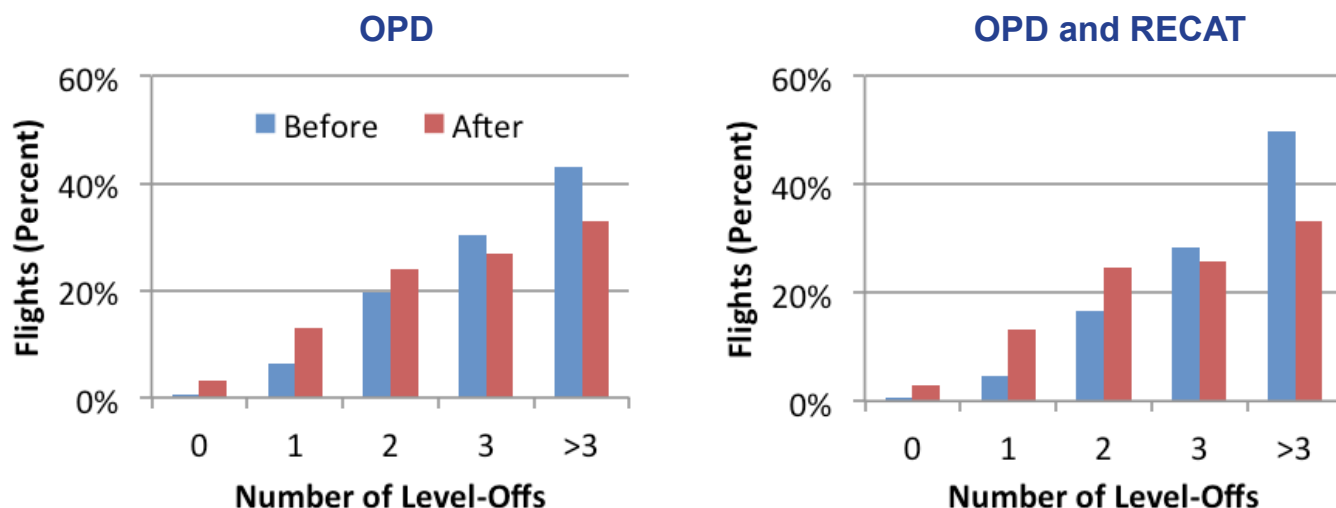


Figure 30 – MEM: Distribution of Flights by Level-offs

use to maintain safety of arriving aircraft as they merge and space them on their final descent to MEM. Compared to the analogous period from the year before, we observed a 55.6 percent decrease in holding events and 10 percent decrease in average holding duration during the first 2 months after RECAT. As a result, in November 2012 and December 2012, operators spent over 4,500 minutes less in holding than they did in November 2011 and December 2011, which represents nearly 50 percent reduction in total holding duration.

In addition, we observed significant efficiency improvements in vertical profiles, with greater benefits realized in IMC when average distance and time in level-flight below TOD decreased 14 and 7 percent after the implementation of the OPD STARs, and 26 percent each after RECAT. There were about 2.5 percent more arrivals

without level-segments., and the average number of level-offs per flight was reduced 12 percent during the first 2 months after implementation of the OPD STARs, and 17 percent during the 2 months after RECAT. There were 10 percent fewer flights with more than three levels-offs immediately after OPD implementation, and almost 17 percent fewer after RECAT.

This analysis did not directly address impacts on controller and pilot workload. Since increased utilization means that aircraft are executing more consistent and predictable trajectories, we can infer additional benefits in terms of reduced controller and pilot communications and potential aircraft interactions. Finally, more consistent trajectories facilitate operator fuel planning, and improve accuracy of estimating fuel consumption.

WAKE Recategorization at Memphis International Airport



Since November 1, 2012, controllers at Memphis Tower are using new spacing criteria to manage separations between aircraft on final approach to, and as they depart from, the airport. The new spacing criteria, based on the Recategorization (RECAT) of Wake Turbulence Separation Categories, is a culmination of decades of research by the FAA, NASA, EUROCONTROL, ICAO and industry partners. There are five traditional wake categories based primarily on aircraft weight: Airbus 380, Heavy, Boeing 757, Large and Small. At Memphis International Airport (MEM), aircraft are now grouped

into six RECAT categories for both arrival and departure separation. Labeled A through F, these categories are based on aircraft weight, approach speed, wing characteristics and lateral control characteristics. Compared to the traditional, the new wake categories provide for less variation in aircraft weight, speed and wake characteristics among the aircraft belonging to the same category. As a result, controllers can now safely apply reduced separation standards between successive aircraft for many of the same aircraft-pair combinations.

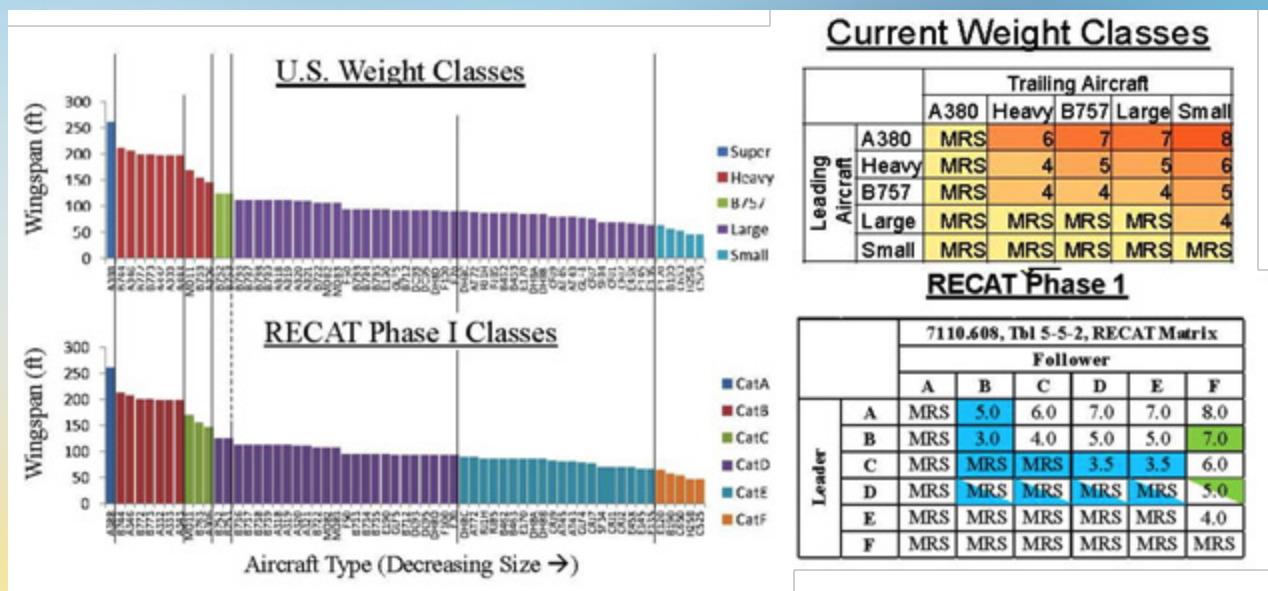


Figure 31 – Current and RECAT Aircraft Classes and Separation Standards (at the Threshold, in nm)

In Notice N JO 7110.608, Guidance for the Implementation of Wake Turbulence Recategorization Separation Standards at Memphis International Airport¹, the FAA describes the key differences between the traditional and the RECAT aircraft categorizations and separation standards. Note that minimum radar separations (MRS) in the terminal area have not changed. The color-coding used in Fig. 31 indicates a direction of change in separations for some or all aircraft pairs as follows:

- White indicates no change
- Blue indicates a decrease
- Green indicates an increase in separations
- Partial color-coding indicates a change for some aircraft pairs within the category
- Full color-coding indicates a change for all aircraft pairs within the category

The FAA plans to expand changes to RECAT separation standards to other airports in 2013 and 2014, including Louisville, Miami, San Francisco and Houston. Other airports will be determined later.

At the time we had to finalize our analyses to meet this report's publication date, RECAT was in use at MEM for just over 3 months. Therefore, the findings reported below are preliminary and meant to provide initial insights into the operational performance impacts. In collaboration with MITRE CAASD and airline partners, the FAA is working on a comprehensive analysis of post-implementation impacts that will be publically available by the end of Fiscal Year (FY) 2013.

For this analysis, we investigated immediate performance impacts on airport efficiency, and efficiency of arriving and departing flights. For airport analysis, we determined pre-RECAT throughput and called rates using FAA's Aviation System Performance Metrics (ASPM) database between November 2011 and January 2012, and post-RECAT rates using data between November 2012 and January 2013. To evaluate impacts on flight efficiency in terminal airspace we used FAA's Performance Data Analysis and Reporting System (PDARS) terminal surveillance data, and on the airport surface we used Airport Surface Detection Equipment-Model X (ASDE-X) surface surveillance data. The pre-RECAT flight efficiency outcomes were evaluated for flights between November and December 2011, and the post-RECAT outcomes for flights between November and December 2012.

To account for seasonal effects and control for operating conditions, we based our analysis on as much data as was available for the same periods before and after RECAT implementation. Additionally, the FAA also implemented seven RNAV STARs and four conventional STARs with Optimal Profile Descent (OPD) procedures

on July 26, 2012. In this analysis, we did not attempt to determine the contribution of each implementation towards the reported outcomes and findings, but addressed operational performance impacts caused by both NextGen implementations and reported the overall changes in performance outcomes.

Operational Performance Assessment

Prior to RECAT implementation, the FAA and its partners have conducted numerous studies investigating its potential performance impacts. In one of those studies, supported by MITRE CAASD, the FAA's ANG Office estimated capacity improvement by modeling Pareto frontiers for MEM with traditional and RECAT aircraft wake categories and FY2014 demand forecast. As illustrated in Fig. 32, the study indicated an improvement potential of up to 9 percent during peak times dominated by arrival flows, and up to 15 percent during peak times dominated by departure flows. During periods with mixed arrival and departure operations, the study indicated a 5 percent capacity improvement potential.

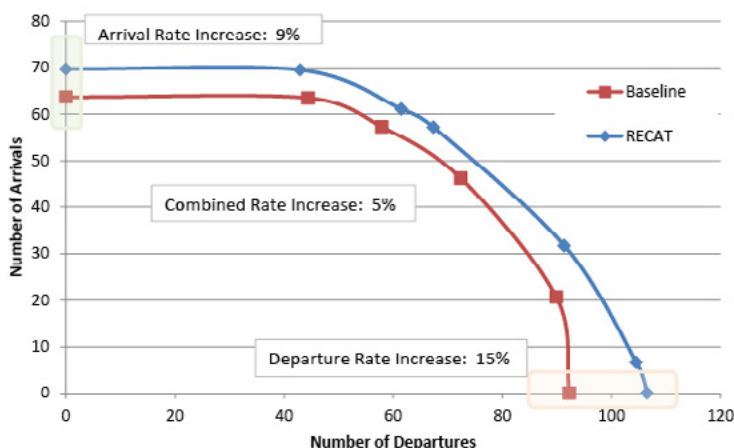


Figure 32 – MEM Pareto Frontier

Due to sensitivity to weather, runway configuration, fleet mix and other operating conditions, change in airport capacity is a lot easier to model than to evaluate in the real world. Typically, the FAA uses Airport Departure and Arrival Rates, ADR and AAR, respectively, to facilitate understanding of capacity related changes across NAS airports. These rates, known as called rates, are set by airport facilities as the number of arrivals and departures each facility can handle for each hour of each day. Called rates are based on expected operating conditions including weather, demand characteristics, and ATC staffing. Clearly, to some extent, ADRs and AARs are subjective measures. However, these empirical rates are good indicators of changes in capacity over time because the facilities do consider the impacts any disruptions (e.g., runway construction projects) or new capabilities

(e.g., CRDA) may have on their ability to handle traffic flows.

Compared to the same period from the year before, average ADRs and AARs have not significantly changed during the first 3 months after RECAT implementation. However, we observed an increase in the rates set for the peak periods in Instrument Meteorological Conditions (IMC). During peak periods, the high-end AARs of 90 arrivals per hour or higher increased 3.1 percent in value over all weather conditions and 6.5 percent in IMC. In addition, the high-end AARs were used 6 percent more often. On the other hand, the high-end ADRs of 80 departures per hour or higher did not significantly increase in value, but were used 11 percent more often.

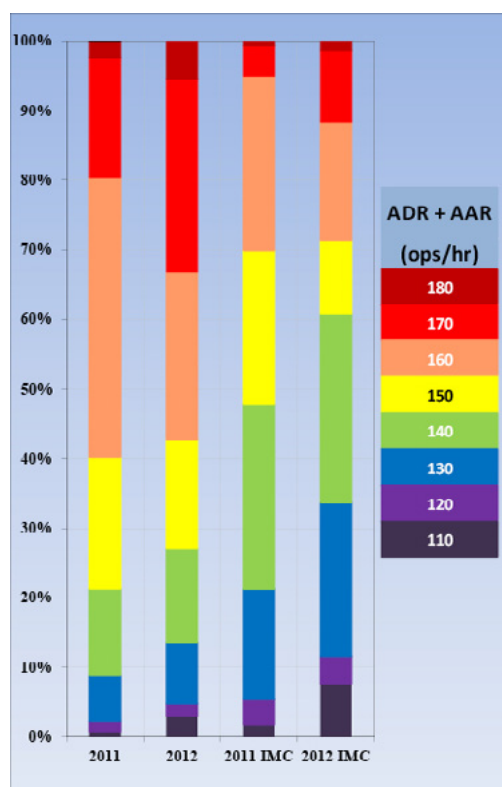


Figure 33 – MEM: Combined Airport Rates

Increases in both high-end rate values and frequency of high-end rate use contributed to an improvement in combined airport rates. As illustrated in Fig. 33, during the 3 months after RECAT implementation, the facility set high-end airport rates of 170 operations per hour or higher about 33 percent of the time overall and 12 percent of the time in IMC. Compared with the same period in the previous year, this translates into an improvement of 13 and 7 percent, respectively.

A quick check of the ADRs and AARs set between February and April 2013 indicated a new record of 100 departures per hour for ADRs and 199 operations per hour for the combined rates. Clearly, as controllers get used to applying the new separation criteria, we will

likely see even higher performance improvements than observed during the 3 months after implementation.

Compared with 2011, MEM experienced a 15 percent decrease in total number of operations in 2012, and a decline in IMC occurrence from 38 to 32 percent. However, as illustrated in Fig. 34, the decrease in demand was not uniform, but predominantly spread across the non-peak hours of the operating day. Average hourly throughput rates maintained the same level during peak hours, while the high-end throughput rates increased 2.3 percent during peak arrival period between 2100 and 0200 local time, and 1.1 percent during peak departure period between 0200 to 0700. In addition, high-end throughput rates increased 8 percent during peak periods in IMC.

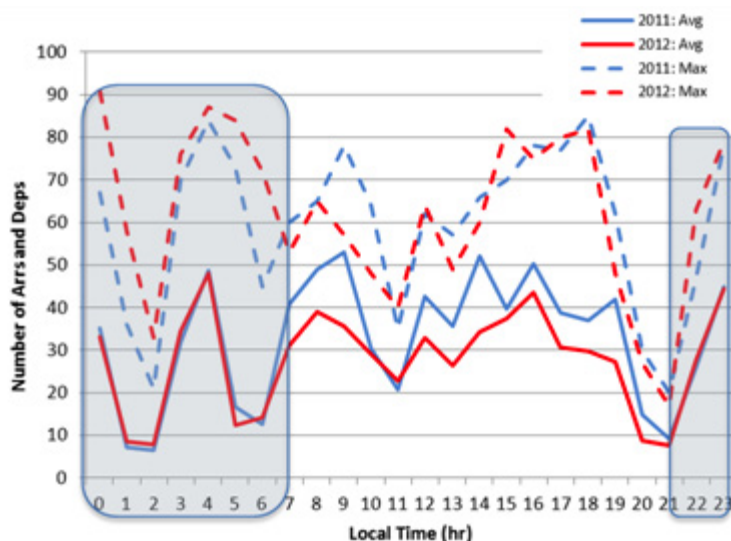


Figure 34 – MEM: Distribution of Airport Operations by Hour of Day

The observed improvement in airport efficiency was driven by tighter aircraft sequences after RECAT was implemented. As illustrated in Fig. 35, the distributions of aircraft spacing shifted to the left for both arrivals and departures. Compared to before RECAT, arrivals are now about 2.5 percent and departures 1.4 percent closer to each other on average as they are landing and departing from the same runway. However, as illustrated in Fig. 36, the distributions of aircraft spacing shifted to the left even more when observed during peak arrival and departure periods with arrivals now about 7.5 percent and departures 5 percent closer to each other on average as they land and depart from the same runway. As a result, despite the overall decrease in demand, airport throughput during peak periods improved, with the most significant improvement realized during IMC.

It is important to point out that the reduced aircraft spacing is a primary operational performance impact from RECAT implementation that directly captures

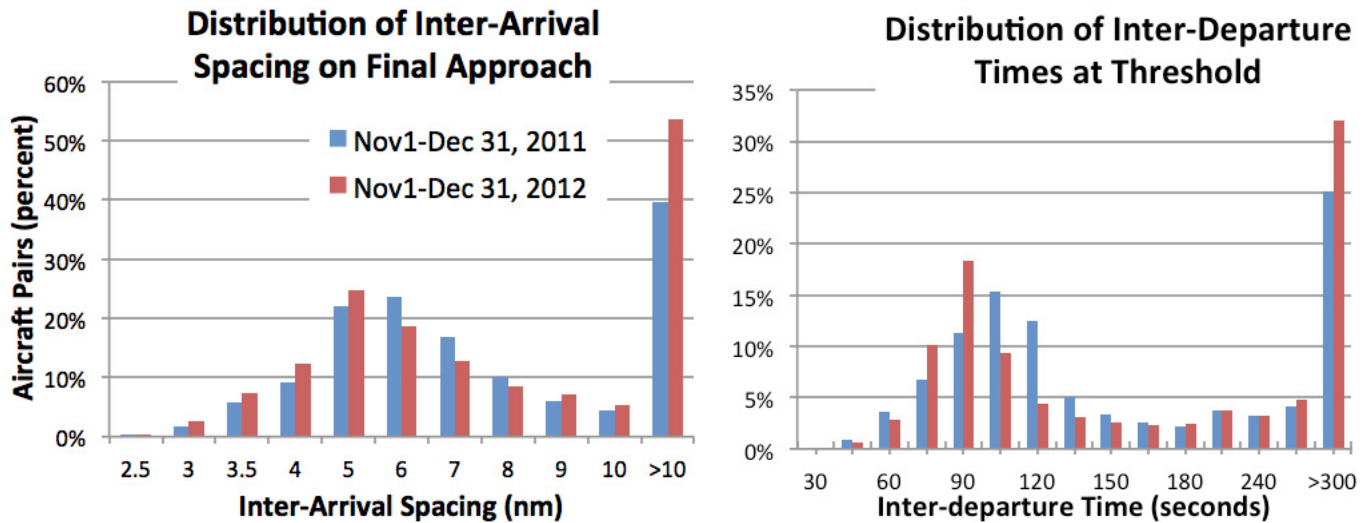


Figure 35 – Distribution of Aircraft Spacing at MEM Before and After RECAT Implementation

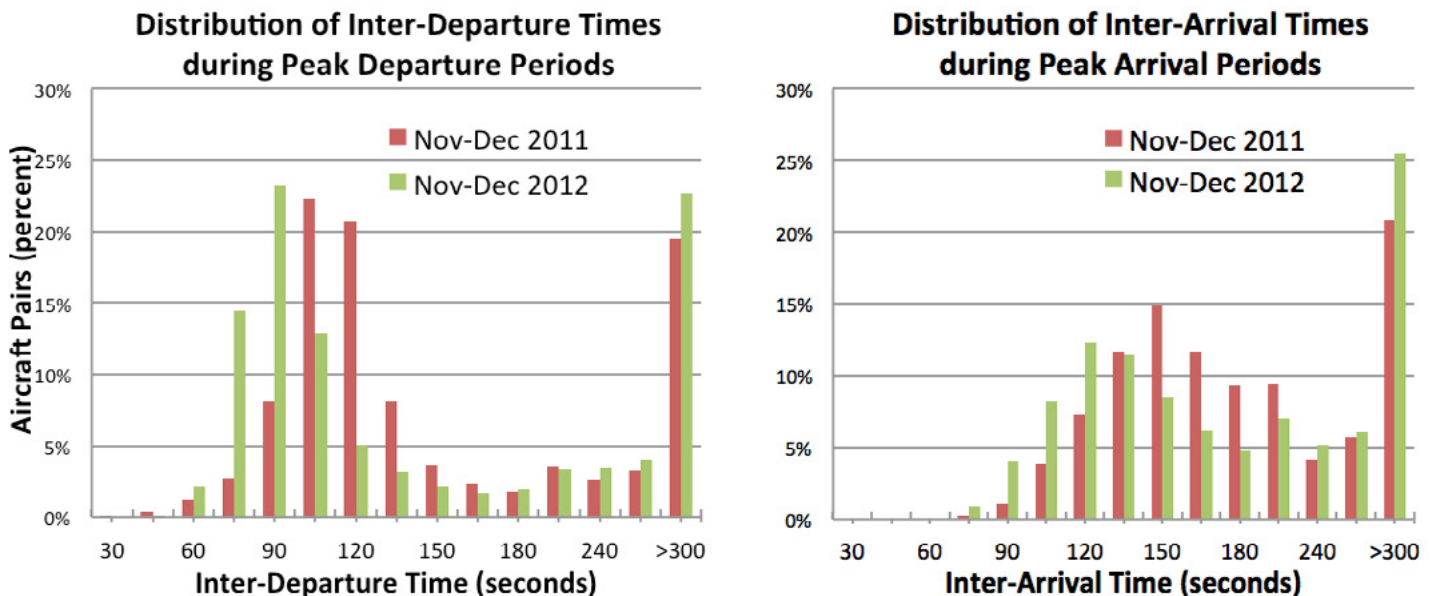


Figure 36 – Distribution of Inter-aircraft Spacing at MEM Before and After RECAT Implementation

actual benefits from reduced separations between the same aircraft types. System and user efficiency related changes in performance outcomes are considered secondary impacts, simply because they are a result of the reduced aircraft spacing.

In addition, even though they are related, airport throughput and aircraft spacing are not equivalent metrics. Hourly airport throughput is predominantly driven by the demand for services, while aircraft spacing by both the demand and the required separation standards. Therefore, in some operational performance assessments such as RECAT, it is not redundant but critical to investigate both metrics to gain full understanding of corresponding performance impacts.

Together with the new RNAV STARs with OPDs implemented in July 2012, RECAT may also have contributed towards improving the efficiency of arrivals in the Memphis terminal airspace. Due to the improved runway capacity, we expected to see less frequent vectoring that the controllers use to manage arrival flows and space aircraft on their final approach as well as shorter excess distance and time due to such vectoring. To analyze the corresponding operational performance impacts, we evaluated changes in several metrics that are typically used to assess efficiency of operations in terminal airspace, including Time, Distance, Level-off Counts and Time in Level-flight. As illustrated in Fig. 37, across all of the evaluated flight efficiency metrics, performance outcomes improved not only on average, but also in terms of their variability and high-end values.

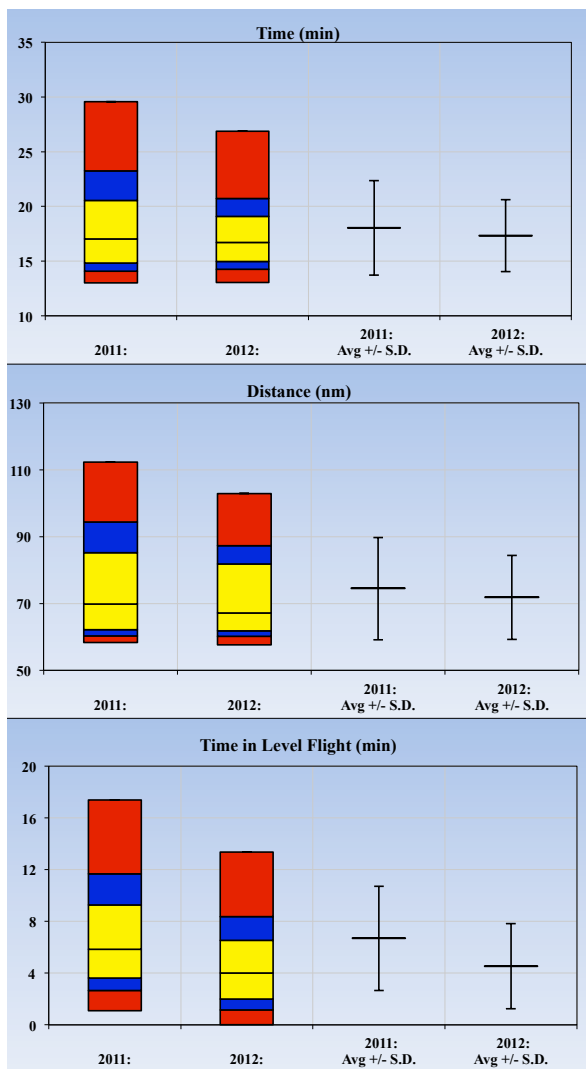


Figure 37– Memphis Terminal Airspace – Arrivals: Flight Efficiency Outcomes

Arrivals to MEM now fly almost 1 minute shorter time and just under 3 nm shorter distances on average, with high-end savings of almost 3 minutes and 10 nm, respectively. Our analysis showed these savings are typically realized within the last 60 nm of MEM where aircraft fly at low altitudes and experience high fuel burn rates. As a result, these savings in time and distance are more significant than they would be if realized further upstream.

Our analysis also showed that arrivals to MEM now fly better vertical profiles as well since the percentage of flights without level-segments was 5 percent higher in 2012 compared to 2011. In addition, time in level-flight was about 2 minutes shorter on average and up to 4 minutes on the high-end.

Since there were no changes in departure paths and flow management practices, we did not expect to observe impacts on flight efficiency of departures in terminal airspace. However, departures experienced significant

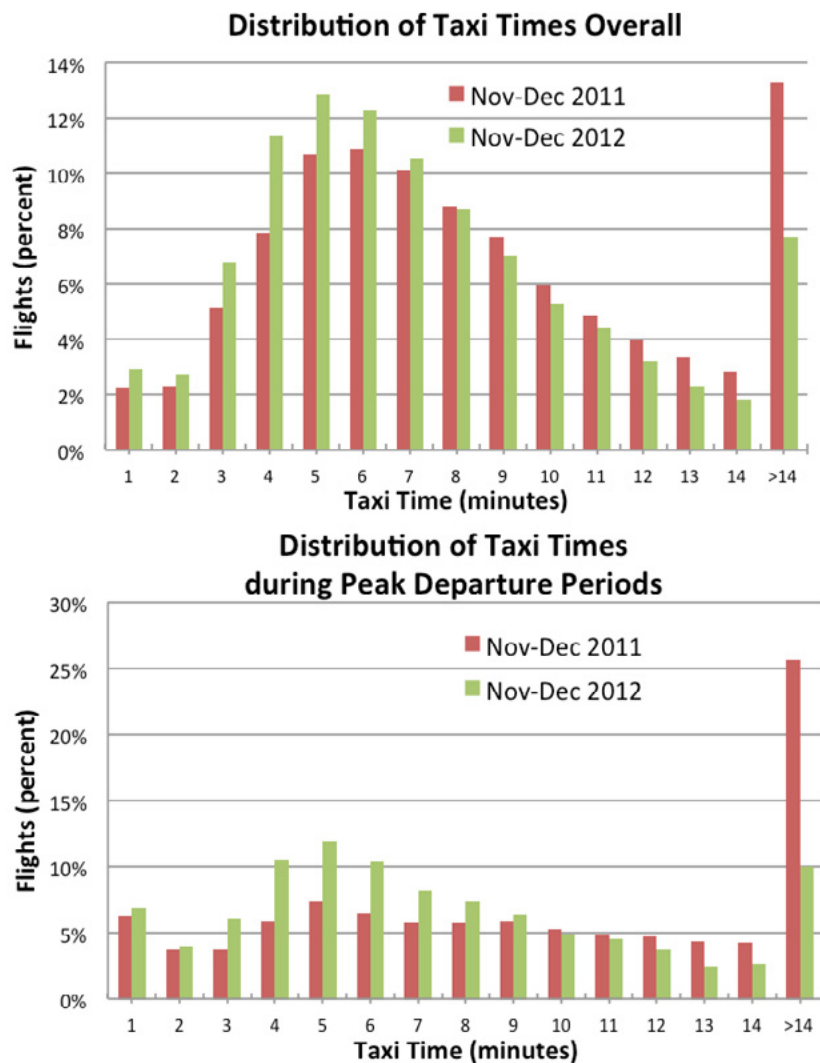


Figure 38 – MEM Surface Ops: Departures: Flight Efficiency Outcomes

improvement in efficiency of their surface operations. As illustrated in Fig. 38, the distributions of taxi-times for departures shifted to the left for all departures throughout the day. Compared to before RECAT, departures are now taxiing over 1 minute shorter on average, a 13 percent reduction. However, this improvement in average taxi-out times is partially driven by the overall lower demand at MEM. Therefore, we also investigated a change in taxi-out times during peak periods, when demand stayed the same on average and slightly increased in the high-end, and observed a more significant reduction in taxi times of 2.8 minutes or 27 percent on average.

The FAA will continue to evaluate and report operational impacts at MEM, including qualitative analysis of controller feedback and quantitative analysis of additional changes in performance outcomes discussed in this report.

Conclusions

After implementing the new RECAT spacing criteria at Memphis, the facility set high-end airport rates at 170 operations per hour or higher about 13 percent more frequently over all weather conditions, and 7 percent more frequently in IMC. High-end AARs of 90 arrivals per hour or higher were not only used 6 percent more frequently during peak periods, but also increased 3.1 percent overall and 6.5 percent in IMC. While high-end ADRs of 80 departures per hour or higher did not significantly increase in value, they were used 11 percent more often.

As controllers get used to applying the new separation criteria, we will likely observe even higher performance improvements than during the 3 months after the implementation. A quick review of the ADRs and AARs set between February 1 and April 30, 2013 confirmed this expectation as it indicated a new record of 100 departures per hour for ADRs and 199 operations per hour for the combined rates.

Compared with the same period a year before, the total number of operations at MEM was 15 percent lower between November 2012 and January 2013, and IMC occurrence declined from 38 to 32 percent of the time. The observed decrease in demand was spread across the non-peak hours of the operating day. During peak hours, average airport throughput maintained the same level, and the high-end throughput rates actually increased 2.3 percent during peak arrival and 1.1 percent during peak departure periods. Moreover, high-end throughput rates increased 8 percent during the peak periods in IMC.

Clearly, despite the overall decrease in demand, MEM achieved an improvement in airport efficiency during peak periods, with the most significant improvement realized during IMC.

The observed improvement in airport efficiency was driven by tighter aircraft sequences after implementing RECAT. In fact, arrivals are now about 2.5 percent and

departures 1.4 percent closer to each other on average as they land and depart from the same runway. During peak arrival and departure periods, the improvement is even higher, 7.5 and 5 percent, respectively.

Together with the new RNAV STARs with OPDs, RECAT contributed to improvements in the efficiency of arrivals in the Memphis terminal airspace, driven by the less frequent vectoring that the controllers use to manage arrival flows and space aircraft on their final approach, as well as shorter excess distance and time due to such vectoring. An arrival saves almost 1 minute and just under 3 nm in the terminal airspace on average, with the high-end savings of almost 3 minutes and 10 nm.

Arrivals into MEM now fly better vertical profiles as well, saving about 2 minutes in level-flight on average and up to 4 minutes on the high-end. The percentage of flights without level-segments is also 5 percent higher. The operators typically realize almost all the terminal efficiency improvements within the last 60 nm of MEM where aircraft fly at lower altitudes and experience high fuel burn rates. As a result, these savings in time and distance are more significant than they would be if realized further upstream.

Departures experienced significant improvement in efficiency of their surface operations. Compared to before RECAT, taxi-out times are now 2.8 minutes or 27 percent shorter during comparable peak departure periods when demand remained at the same level on average and slightly increased at the high-end. Once again, aircraft are taking advantage of the reduced separations and clustering closer to each other, which results in improved efficiency of surface operations.

References

¹FAA Notice N JO 7110.608, Guidance for the Implementation of Wake Turbulence Recategorization Separation Standards at Memphis International Airport, URL: <http://www.faa.gov/documentLibrary/media/Notice/N7110.608.pdf>

New York Metropolitan Area Regional Arrival Performance Analysis



With a goal of improving operations in one of the most heavily congested regions in NAS, the FAA introduced a series of operational, technological, and policy changes in the greater New York, New Jersey, and Philadelphia metropolitan area between 2007 and 2012. A timeline in Fig. 39 indicates when specific changes were introduced and Appendix A provides additional details about these recent implementations.

As shown in Fig. 39, the starred items represent one policy and several operational changes associated with the New York/New Jersey/Philadelphia Metropolitan Area Airspace Redesign project or NY Redesign project. The NY Redesign project is one of the largest, most complex projects the FAA has ever conducted. The sweeping changes to airspace and routes in the metropolitan area impact the operational structure from Canada to Florida,

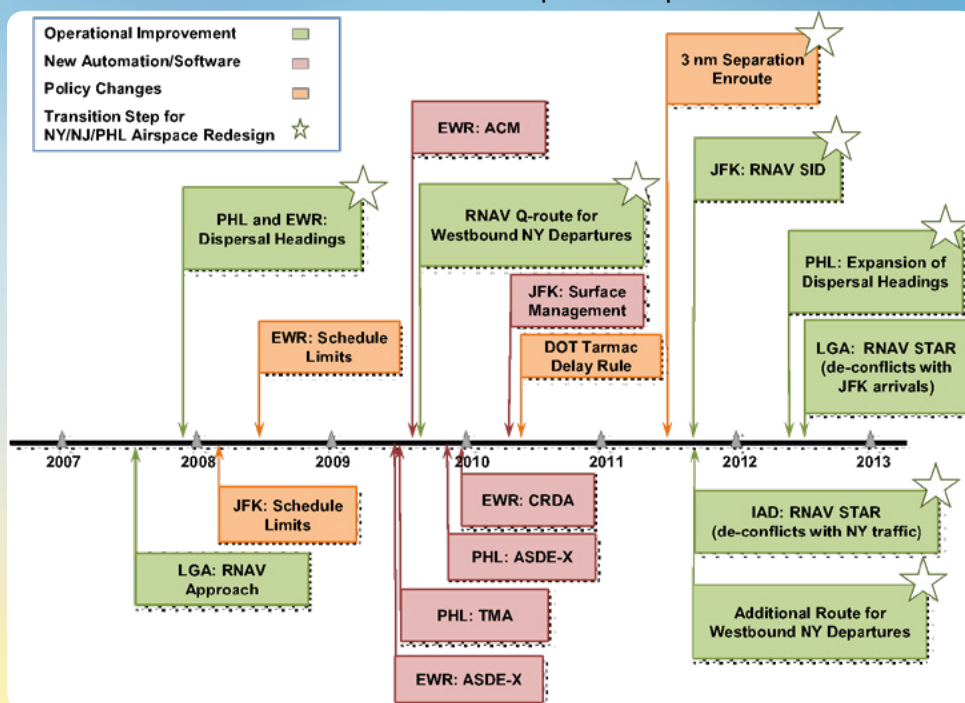


Figure 39 – New York Metropolitan Area Timeline of Improvements

and as far west as Chicago. The scale of the project requires a staged implementation through 2016, with stages completed to date accounting for approximately 30 percent of the overall plan. It is important to point out that the primary purpose of these initial stages was to set the foundation for the remaining implementations, and that the full benefits will not be achieved until the project is fully completed.

The NY Redesign project lays the foundation for leveraging NextGen capabilities in the New York metropolitan area. The new operational structure removes choke points, streamlines traffic flows, and relies on NextGen initiatives such as Performance Based Navigation (PBN) and improved automation and software capabilities, as well as policy changes such as expanded terminal rules.

This section describes first of two complementary performance impact analyses applicable to the New York metropolitan area. It addressed regional impacts on performance of arrivals into the area, and did not focus on any particular implementation but investigated overall impacts from all of the recent implementations. The analysis described in the following section, on the other hand, focused on the impacts of a particular recent implementation—a new aircraft separation policy in low altitude en route airspace. In the first analysis, we investigated impacts onto all arrivals into the area, and in the second, we investigated impacts applicable only to the sectors and flights directly affected by the change. As a result, the outcomes of the two analyses are not additive, but complementary.

Since a significant number of the recent improvements aimed to alleviate problems faced by arriving flights, our regional analysis focused on arrivals into the four largest airports directly affected by New York metropolitan area improvements: Newark International Airport (EWR), John F. Kennedy International Airport (JFK), LaGuardia Airport (LGA), and Philadelphia International Airport (PHL). We gathered data between April 2008 and December 2012 from a variety of sources including Aviation System Performance Metrics (ASPM), Airline Service Quality



**Figure 40 – New York Region:
Average Daily Arrivals**

**Table 15 – Change in New York Area Region
Performance Outcomes, as of Dec. 2012**

Observed Performance Metrics	Change in Outcomes Relative to January 2011
Total ZNY Vector Delay (attributable to ZNY)	-41%
Total Hold Durations (in ZNY)	-51%
Average Block Delay	-1.9 min
Average Pushback Delay for Arrivals	-1.2 min
Average At Gate Delay for Arrivals	-3.1 min
Average Taxi-Out Time for Arrivals	-1.0 min
Average Taxi-In Time	-0.6 min
Average Actual Block Time	-1.4 min
Average Scheduled Time	+0.5 min
Average Arrival Throughput	-0.24%

Performance (ASQP), and Traffic Flow Management System (TFMS). We evaluated magnitude and frequency of delays, flight durations by phase of flight, and actual and scheduled airport throughput. We weighted the outcomes by actual traffic levels, and aggregated them to the New York regional level. Unless noted otherwise, we also adjusted all outcomes to account for seasonal, monthly and day-of-week variations.

Operational Performance Assessment

Demand, or airport throughput, is one of the most important factors influencing performance outcomes. In Fig. 40, we present a multi-year trend of scheduled daily arrivals into the four airports during busy periods between 6 AM and 10 PM. Although not as smooth, the curve representing actual daily arrivals follows the same trend. Clearly, after a decline in operations between 2008 and 2010, arrival demand has remained stable since the end of 2010. In fact, scheduled daily arrivals remained within just over 1 percent of its lowest level in late 2010. Since demand in 2011 and 2012 remained relatively unchanged, we can conclude that any significant changes in regional performance outcomes after 2010 were not driven by the changes in demand.

Table 15 summarizes the changes in key performance outcomes between January 2011 and December 2012. While scheduled arrival demand remained relatively unchanged since January 2011, distinct improvements can be seen across all phases of flight for these arrivals. Taxi-in times decreased for arrivals into New York, as did their departure delays and taxi-out times at their origin airports.

Additionally, while scheduled block times increased 0.5 minutes, actual block times decreased 1.4 minutes on

average. Since scheduled block times represent gross estimates used to manage reliability of schedules and crew and airframe rotations, they include buffers outside control of the operational improvements delivered by the NY Redesign Project or NextGen. As a result, a change in scheduled block times can be an indicator of system efficiency, but only if observed across a long period. Consistent observations of improved actual block times are necessary for carriers to adjust scheduled block times accordingly. As a result, change in actual block times is a better indicator of true change in flight efficiency that may have been influenced by the recent operational improvements.

However, the most dramatic changes in performance concerned the New York airspace, which now experiences less congestion. We observed a significant decrease in total hold durations in New York ARTCC (ZNY), and in vector delays accumulated by flights into the New York area that is attributable to ZNY. Some of the improvements associated with decreased congestion in ZNY were likely due to the new separation policy affecting low altitude en route airspace, and Adjacent Center Metering (ACM) into EWR. Likewise, a significant increase in the use of time-based metering (TBM) beginning in the summer of 2010 may have also influenced the observed changes in performance outcomes. At this level, however, it is impossible to accurately identify all of the actual causes that delivered these performance improvements. Assessing causality and the contribution of each cause to the overall

Table 16 – New York Region: Correlation between Observed Arrival Rates and Performance Outcomes

Observed Performance Metrics	2008 to 2010	2011+
Total ZNY Vector Delay (Counts)	0.53 (0.62)	-0.05 (0.04)
Total ZNY Hold Durations (Counts)	0.53 (0.47)	0.00 (-0.05)
Average Block Delay	0.44	0.15
Average Pushback Delay for Arrivals	0.38	0.13
Average At Gate Delay for Arrivals	0.44	0.15
Average Taxi-Out Time for Arrivals	0.42	-0.27
Average Taxi-In Time	0.67	0.09
Average Actual Block Time	0.68	0.29

change in performance outcomes requires a more detailed analysis. Such diagnostic analysis would have to account for other potential drivers including weather, and address arrival flows through ZNY as well as flows through the facilities delivering arrival traffic to the New York TRACON (N90).

Fig. 41 depicts the time series for each of the observed performance outcomes standardized to a 0 - 1 scale, where 0 represents the minimum and 1 represents the maximum values of each outcome between April 2008 and December 2012. The black vertical bars, set at January 2011 and December 2012, encapsulate the period over which we evaluated performance changes summarized in Table 1. They also facilitate visualization

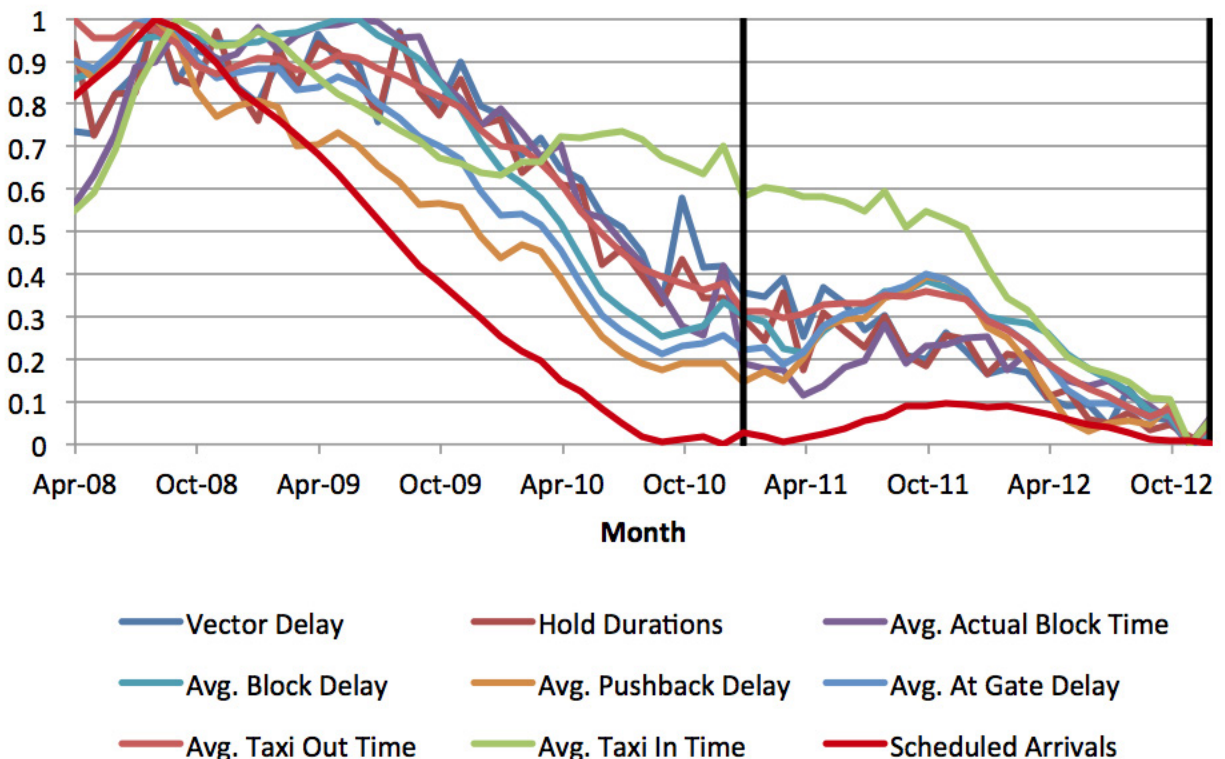


Figure 41 – New York Region: Standardized Arrival Performance Outcomes

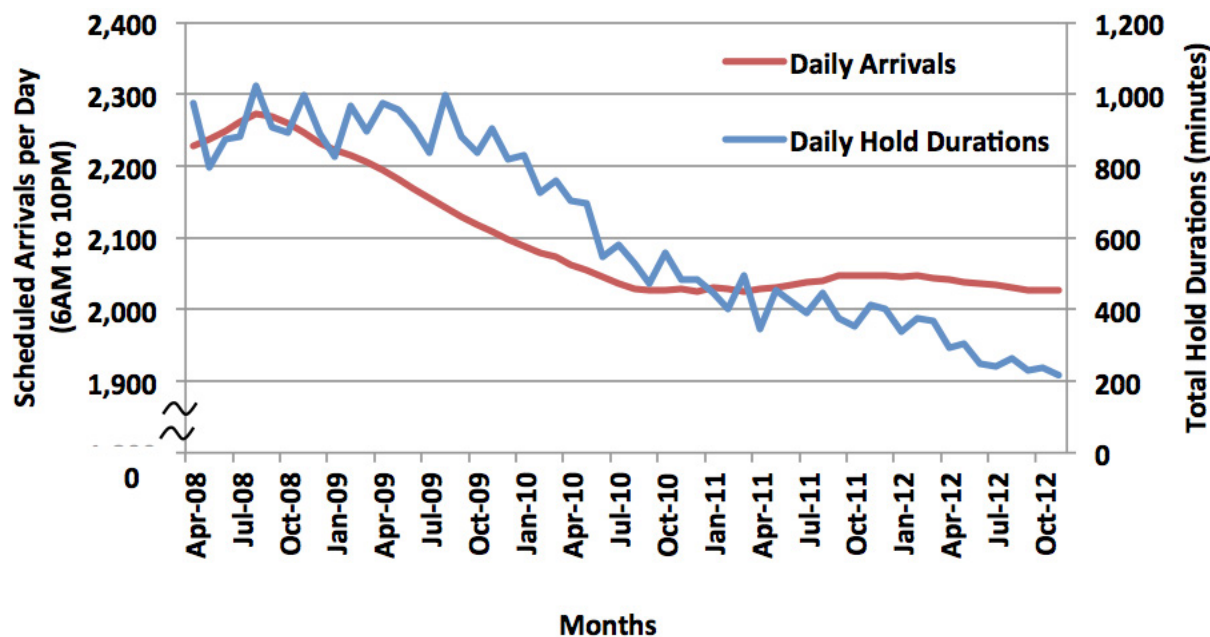


Figure 42 – New York Region: Hold and Arrival Trends

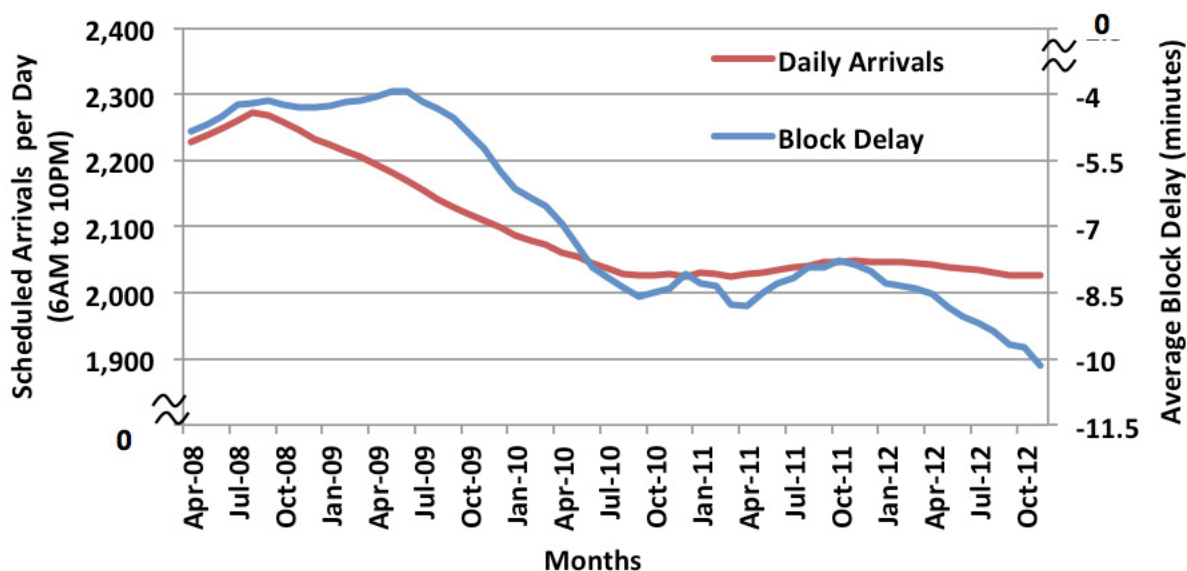


Figure 43 – New York Region: Block Delay and Scheduled Arrival Trends

of performance impacts discussed above, including a steady decline since the beginning of 2011 and the fact that all of the observed performance outcomes were at their lowest point at the end of 2012. Arrival demand, on the other hand, remained within 1.2 percent of its lowest point observed in late 2010. Clearly, in late 2010 or early 2011, the relationship between performance outcomes and arrival demand changed.

To understand this change, we evaluated the correlation between observed arrival rates and individual performance outcomes using unadjusted data between 2008 and 2012. In Table 16, we present the findings using the following color-coding scheme:

- Red for values below 0.3 indicating a weak correlation,

- Yellow for values between 0.3 and 0.5 indicating a moderate correlation, and
- Green for values above 0.5 indicating a strong correlation.

Between 2008 and 2010, there was a moderate to strong correlation between observed arrival rates and evaluated performance outcomes. However, after 2010, the same performance outcomes became entirely uncorrelated with demand. In other words, demand was a fairly reliable predictor of regional performance outcomes between 2008 and 2010, but was not a reliable predictor of outcomes between 2011 and 2012.

Fig. 42 illustrates the change in the relationship between arrival demand and performance outcomes using

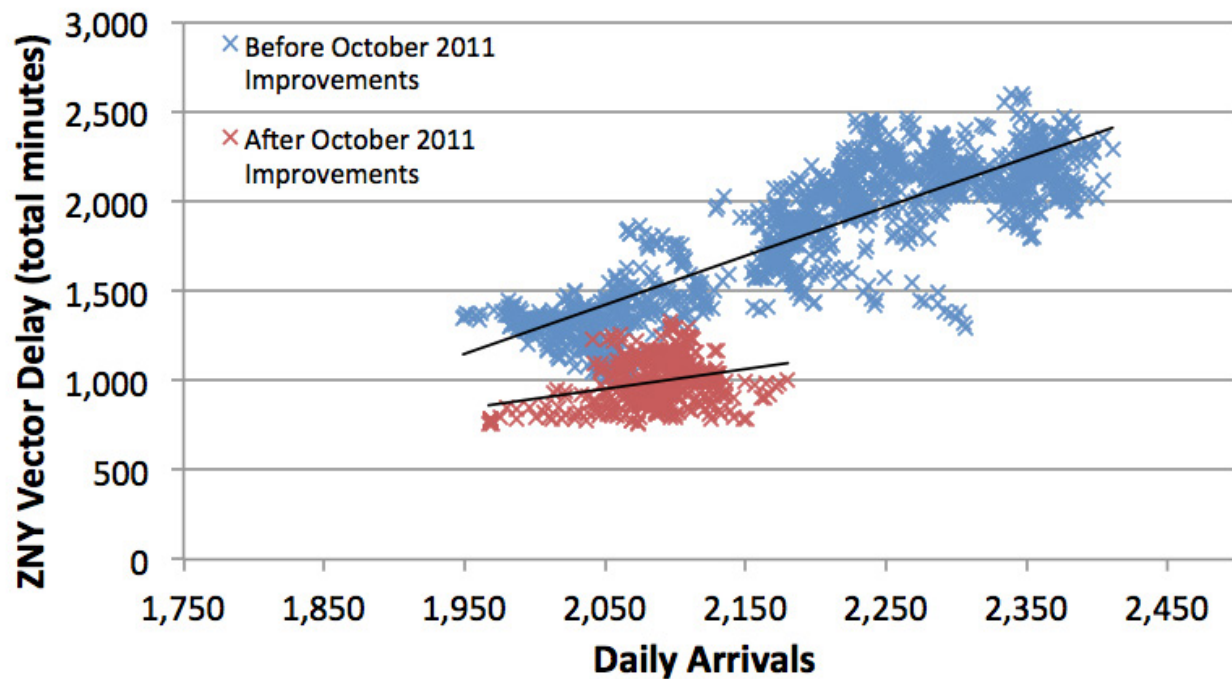


Figure 44 – New York Region: Daily Vector Delays

Total Hold Durations. Before 2011, hold durations and arrival rates exhibited similar trends, but these trends started diverging more significantly in 2011. Arrival rates remained relatively unchanged after 2011, while hold durations continued to decline.

Similarly, Fig. 43 illustrates the change in the relationship between arrival demand and block delay. In this case, there is an even more significant divergence in trends after October 2011, characterized by a steep decline in block delay and only minor variations in arrival demand. Interestingly, the timing of this change in the relationship between arrival demand and block delay coincides with three operational improvements in the New York metropolitan area; however, the same change was likely influenced by other developments such as the previously mentioned change in use of flow management initiatives.

In Fig. 44, we present another way of depicting the change in the relationship between arrival demand and performance outcomes using Vector Delays. This chart illustrates two important findings: (1) for the same arrival demand, vector delays were noticeably lower after October 2011; and (2) for the same marginal increase in arrival demand, a corresponding increase in vector delays was noticeably lower after October 2011.

Finally, each of the unadjusted observed performance outcomes retained a strong correlation with others throughout the entire studied period. For example, before 2011, vector delays were highly correlated with nearly every other observed performance outcome. The correlation with Taxi-in Times was medium at 0.42, while the correlations with all other outcomes were strong—

between 0.67 and 0.93. After 2011, the correlation between vector delays and every other evaluated performance outcome was strong, with values between 0.58 and 0.87. These strong correlations between performance outcomes, combined with weakened correlation between outcomes and arrival demand, indicate that recent improvements are having a positive impact on arrivals into the New York area.

Conclusions

Post-implementation impact analyses are typically complicated by the strong correlation between performance outcomes and demand. It is often difficult, and sometimes even impossible, to determine the extent to which observed performance impacts may have been caused by a new operational improvement as opposed to the coinciding changes in demand. However, between 2011 and 2012, arrival demand in the New York metropolitan area remained within 1.2 percent of its lowest level observed in late 2010/early 2011. After a long period of a steady decrease in demand, we finally had an opportunity to conduct an impact assessment without having to control for, or factor out, demand's influence on performance outcomes.

Numerous operational improvements have recently been implemented in the New York area. Rather than investigate individual improvements and their customized impacts, this assessment focused on their synergy and corresponding regional impacts. Using multiple data sources, we evaluated actual and scheduled airport throughput between 2008 and 2012, as well as magnitude and frequency of delays, and flight durations

by phase of flight. We weighted the outcomes by actual traffic levels, adjusted them to account for seasonal, monthly and day-of-week variations, and aggregated them to the New York regional level.

Since January 2011, there has been a considerable reduction in both times and delays across all phases of flight for arrivals into the largest four airports in the area. By the end of 2012, total vector delays were 41 percent lower and hold durations 51 percent lower. On average, taxi-in times decreased 0.6 minutes for arrivals into New York, while the gate delays and taxi-out times at origin airports decreased 1 minute and 3.1 minutes. Actual block times were 1.4 minutes lower and block delays 1.9 minutes lower on average.

In addition, a detailed investigation of the correlation

between performance outcomes and demand confirmed a significant change in the underlying relationships. Prior to 2011, performance outcomes were very sensitive to a change in demand and mirrored demand's trend with minor variations. After 2011, we observed significant improvements across all key performance outcomes and only minor variations in demand. This finding indicates a possible systemic change in the New York area, most likely caused by the recently implemented operational improvements that resulted in quantifiable benefits at a regional level.

This analysis represents a first step in a comprehensive assessment of performance impacts in the New York metropolitan area. In the future, we will complete the regional assessment by investigating the impacts on departures.

Appendix: New York Metropolitan Area Improvements Since 2007

Improvement	Date	Location	Description
LGA: RNAV Approach	Aug. 2007	LGA	Overlay of the Localizer Type Directional Aid (LDA), with an RNAV-Z procedure. The PBN approach is intended to encourage increased usage of the LDA, with the added benefit of reduced noise for communities under the ILS.
PHL and EWR: Dispersal Headings	Dec. 2007	PHL/EWR	Part of NY Redesign Stage 1: Initial implementation of dispersal headings at PHL included 2 of the 3 headings in the west configuration and 2 of the 4 in the east.
EWR: ASDE-X	July 2009	EWR	Fuses data on the surface to provide controllers with precise location of aircraft on the surface and within 5 miles of the airport.
PHL: ASDE-X	Nov. 2009	PHL	Fuses data on the surface to provide controllers with precise location of aircraft on the surface and within 5 miles of the airport.
PHL: TMA	Mid-2009	PHL	A ground tool used by air traffic management to calculate more strategic flight trajectories and solutions.
RNAV Q-route for Westbound NY Departures	May 2009	Region	Part of NY Redesign Stage 1: J80 serves westbound flights out of the NY/NJ/PHL area. This improvement created another jet route (J80N), to the north and parallel to J80, which is now also a Q-route (Aug 2009). This change positioned the system for the Expansion of the Westgate.
EWR: ACM	Aug. 2009	EWR	An inter-facility component of Traffic Management Advisor (TMA) that enables collaboration between neighboring facilities while metering arrivals in at airport.
EWR: CRDA	Dec. 2009	EWR	Allows for a simultaneous, dual-stream arrival on crossing runways.
JFK: Surface Management	March 2010	JFK	New software to better manage surface traffic. Particularly useful in light of the construction and resurfacing projects.
3 nm Separation En route	May 2011	Region	Part of NY Redesign Stage 2A: The separation requirements are reduced from 5-7 miles down to 3 miles. This allows more efficient crossing of flows between transitioning flights.
IAD: RNAV STAR (de-conflicts with NY traffic)	Oct. 2011	Region	Part of NY Redesign Stage 2A: Washington (to IAD) offsets create lateral separation of IAD descending flights from climbing NY departures filing J6 (such as those headed to Texas), allowing the NY departures to reach more efficient altitudes faster.

Improvement	Date	Location	Description
Additional Route for Westbound NY Departures	Oct. 2011	Region	Part of NY Redesign Stage 2A: The ELIOT departure fix, which fed 4 jet airways, is split into two fixes, feeding 2 jet airways each. This facilitates more efficient access to the westbound high altitude route structure and alleviates traffic management restrictions that cause delays.
JFK: RNAV SID	Oct. 2011	JFK/Region	Part of NY Redesign Stage 2A: A new departure procedure called DEEZZ “wraps” JFK departures around the north side of the airport with left turns. These flights join the west departure airways aligned with and above departures from other NY metro area airports to the west. This procedure reduces complexity in the airspace supporting the westbound route structure.
PHL: Expansion of Dispersal Headings	May 2012	PHL	NY Redesign Stage 2B: Full implementation of dispersal headings at PHL, including one additional west bound heading making a total of three headings, and two additional east bound headings making a total of four headings. Full usage and final distribution of traffic across the headings is dependent on the implementation of Stage 4 changes.
LGA: RNAV STAR (de-conflicts with JFK arrivals)	2012	LGA/JFK	Flights departing Runway 13 at LGA may use this procedure, which lets JFK arrivals operate independently of the LGA departures.
Policy Changes			
JFK: Schedule Limits	Feb. 2008	JFK	Schedule limits were implemented to reduce the number of allowed operations during the busiest times of the day.
EWR: Schedule Limits	June 2008	EWR	Schedule limits were implemented to reduce the number of allowed operations during the busiest times of the day.
DOT Tarmac Delay Rule	April 29, 2010	All	Commonly referred to as the “3-Hour Tarmac Rule” prohibits U.S. airlines operating domestic flights from permitting an aircraft to remain on the tarmac for more than 3 hours without deplaning passengers. Violators are subject to fines.

Separation Reduction in New York Low-altitude Airspace



Air traffic controllers typically use a 5 nm separation standard in the en route airspace. However, in enroute airspace below 18,000 feet, current procedures allow controllers to use a reduced separation standard of 3 nm provided the aircraft remain within 40 miles of radar at all times and en route automation is adapted to provide higher quality surveillance data displayed on controller scopes.

The use of 3 nm separation standard has been limited because en route radars are typically located further apart than required. Previously, en route automation could typically not be adapted to integrate as many radar feeds as required. However, recent improvements in en route automation now provide high quality surveillance data to the controllers. Combined with a dense network of en route radars that provide surveillance of the congested airspace in the northeast, these improvements enabled an expansion of the 3 nm separation standard to 15 low

altitude en route sectors in the New York center (ZNY) in May 2011.

Reducing the required minimum separation from 5 to 3 miles facilitates more efficient traffic management. It accommodates additional routes in constrained airspace, as well as de-conflicting routes. The result is a reduction in the use of vectoring to space and merge traffic flows with fewer additional miles flown when necessary.

In addition, as shown in Fig. 45, the space between successive descending aircraft in an arrival flow compresses as the faster aircraft flying at higher altitude overtake the slower preceding aircraft at lower altitudes. Since the rate of compression varies with altitude and aircraft performance, controllers will normally use additional spacing to ensure the minimum separation standard is met. Managing arrivals is more efficient when applying a reduced separation minimum because

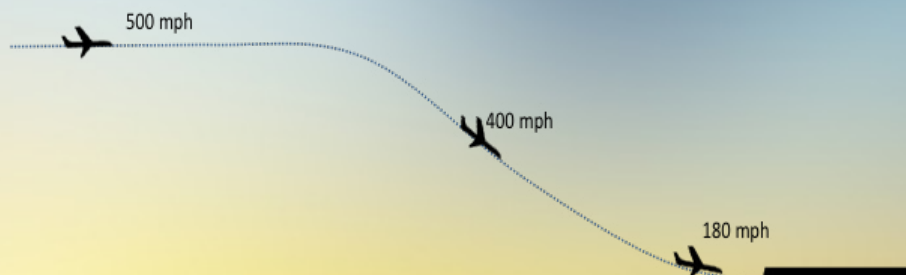


Figure 45 – Example: Lead Aircraft Slower than Following Aircraft

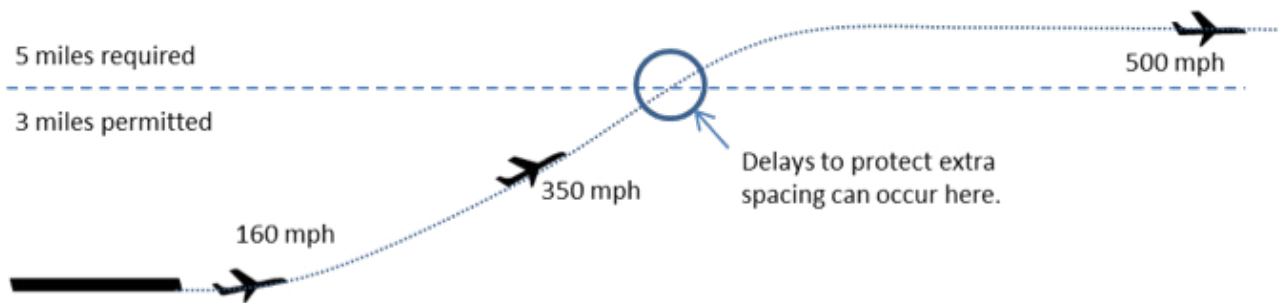


Figure 46 – Delay Caused by Different Separation Standards in Adjacent Sectors

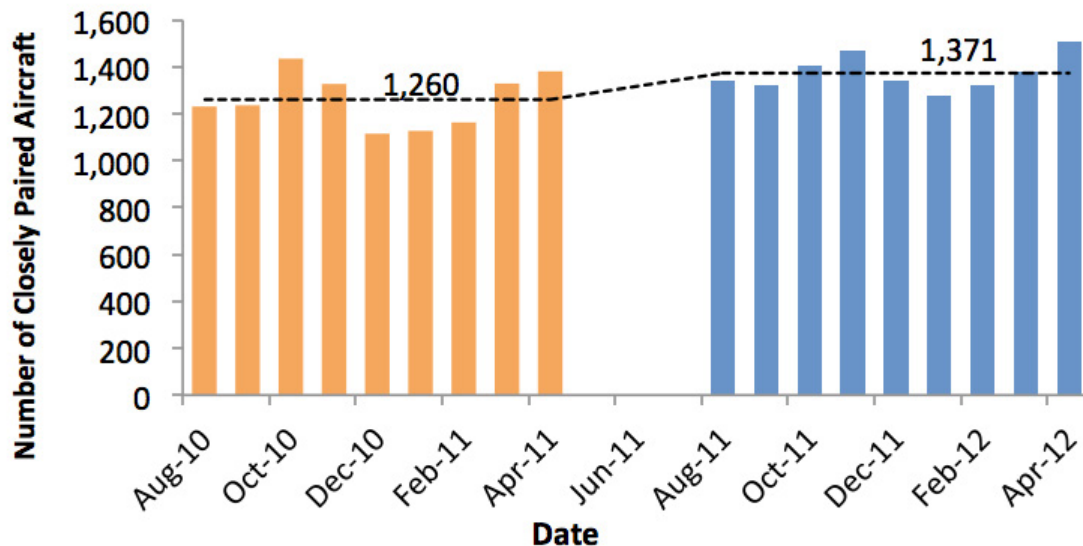


Figure 47 – Pairs of Closely Spaced Flights with 9-month Average

it facilitates use of tighter spacing between successive descending aircraft.

As illustrated in Fig. 46, when a departure controller uses 3 nm-separations, and hands-off aircraft to an en route controller who uses 5 nm instead, the departure controller will need to add a buffer to assure a conflict-free hand-off. When the en route controller can also use 3 nm, the extra spacing does not have to be applied.

We can investigate actual use of reduced separations by studying surveillance data and proximity of flown trajectories. Reduced separations are likely to lead to improved operator efficiency, as controllers issue fewer maneuvers, such as vectoring and holding, to ensure proper spacing. System efficiency is likely to improve as well through a possible increase in effective airspace capacity and a reduction in delays, especially during busy times of the day.

To assess performance impacts after the expansion of 3-mile separation procedures in low-altitude airspace, we used surveillance data and analyzed trajectories that

traversed the ZNY sectors affected by the new policy. We evaluated and compared spacing between aircraft during 9 months before and after implementation, and identified close pairs of aircraft on crossing flows. We also analyzed changes in airspace throughput, and occurrences of vectoring or holding during the year before and the year after implementation.

Operational Performance Assessment

We identified closely spaced pairs of aircraft by estimating the closest distance between simultaneous radar returns, and determining the instances of two aircraft passing each other within 1,000 ft vertically, 7 nm laterally and 5 seconds. As illustrated in Fig. 47, we observed a 9 percent increase in occurrences of closely spaced aircraft after the implementation of the new rules.

There was a significant improvement in time that flights spent holding or vectoring while waiting to enter low altitude ZNY sectors. Even though generally infrequent in this airspace, holding and vectoring require significant air traffic controller attention, and cause negative and

significant impacts on flight efficiency. Compared to the year before implementation, holding duration decreased 20 percent and excess time due to vectoring decreased 19 percent during the year after implementation. Sectors that predominately handle departure and crossing flows experienced the most significant improvement. Although not directly evaluated, the resulting decrease in complexity of traffic patterns likely caused a reduction in air traffic controller workload too.

This positive impact on holding and vectoring may have also been influenced by other factors such as overall demand and weather at the destination airports. By the time flights enter the low-altitude sectors in ZNY, most of the traffic management initiatives for demand or weather have already been applied. It is important to point out that we observed the most significant impact on vectoring in the airspace feeding the sectors affected by the new policy. However, impact on vectoring was not statistically significant within the affected sectors.

Finally, even though overall demand was steady, there was a 2 percent increase in the number of flights entering affected ZNY sectors during the busiest periods.

Conclusions

Unlike the regional assessment which investigated overall impacts from all of the recent implementations on the performance of arrivals in the New York metropolitan area, this assessment focused on the impacts of

a particular recent implementation—a new aircraft separation policy in low altitude en route airspace. As such, it investigated impacts applicable only to the sectors and flights directly affected by the change.

Aircraft are flying within 1,000 ft vertically, 7 nm laterally and 5 seconds from each other about 9 percent more often after the implementation of the new separation policy. While waiting to enter low altitude ZNY sectors, flights now experience 20 percent shorter holding durations as well as 19 percent savings in excess time due to vectoring. The most significant impact on vectoring was realized in the airspace feeding the sectors affected by the new policy, especially in sectors that predominately handle departure and crossing flows. However, the impact on vectoring was not statistically significant within the sectors directly affected by the separation reduction.

There were no significant changes in demand; however, the number of flights entering affected ZNY sectors during the busiest periods increased 2 percent. While these improvements in performance were likely caused by the newly implemented separation policy in low altitude en route airspace, they were also likely influenced by other factors such as overall demand and weather at the destination airports. A more detailed, diagnostic analysis is required to positively assign causality.

Lower Runway Visual Range Minima Operations and Simultaneous Offset Instrument Approaches at San Francisco International Airport



Access to airport runways during marginal weather is a key driver of NAS performance and a foundational premise for NextGen. Minimum weather, crew, and airframe operating requirements ensure safety under adverse conditions, but can also limit airport effective capacity. When new technologies or procedures enable the safe reduction of these minima they provide increased access to airports and associated benefits.

Low visibility and clouds at San Francisco International Airport (SFO) often restricts arrivals and departures. The introduction of two improvements addresses this problem by enabling the use of two runways in adverse weather, where previously the airport was limited to one runway. These improvements are the lowering of the Runway Visual Range (RVR) for departures and Simultaneous Offset Instrument Approach (SOIA) procedures for arrivals.

RVR visibility sensors measure RVR in regular intervals as the maximum visible distance down a runway from its approach end. Through Order 6560.10C RVR, dated January 20, 2011, the FAA revised requirements to allow the use of one sensor to serve more than one runway for all departures and arrivals. The order enabled shared RVR between SFO parallel runways to visibility of 500 ft. Previously, when visibility fell below 1,600 ft, aircraft could depart from only one runway, 1R. After the revision, Runway 1L's RVR minima decreased from 1,600 ft to 500 ft, allowing the use of both runways for

departures in these conditions.

Prior to reducing RVR minima for Runway 1L at SFO, all departures had to be moved to Runway 1R during times with visibility below 0.25 mile. This resulted in reduced departure efficiency since aircraft could only be queued to depart from one runway. Now that the airport can support departures on both runways with visibility as low as 500 ft, we expect increased airport throughput under these conditions. We also expect improved surface performance outcomes for aircraft waiting to depart.

SOIA approaches have been in operation at SFO since

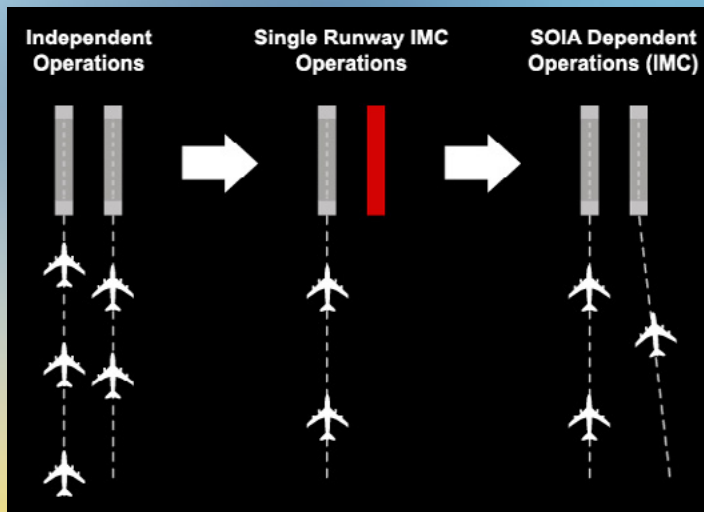


Figure 48 – Configuration Transition to SOIA

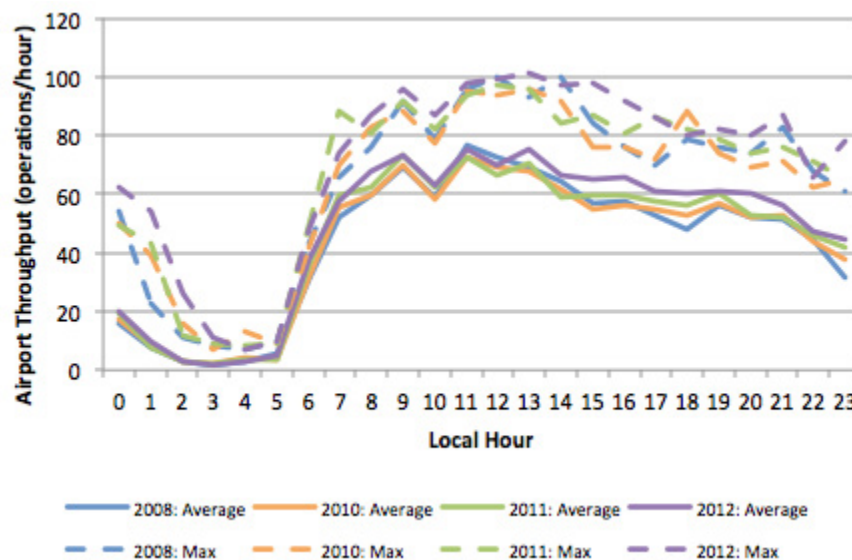


Figure 49 – SFO: Distribution of Airport Operations by Hour of Day

2004 with a minimum required cloud ceiling of 2,100 ft and visibility of 4 sm. As illustrated in Fig. 48, SOIA utilizes a straight-in course to one of the runways, and up to a 3 degree offset to the other parallel runway. When conducting simultaneous approaches, operators using SOIA at SFO utilize an Instrument Landing System (ILS) Precision Runway Monitor (PRM) approach to Runway 28L, and a Localizer Type Directional Aid (LDA) PRM approach with glideslope to Runway 28R. Aircraft conducting the LDA approach to 28R are required to transition to visual separation when in visual conditions below the cloud ceiling and after the LDA Decision Altitude (DA-1,140 ft mean sea level). The SOIA procedure requires that the aircraft conducting the LDA approach to Runway 28R is paired with and trailing the aircraft conducting the ILS approach to Runway 28L. When the LDA aircraft exits the clouds, its crew must visually acquire the ILS aircraft and maintain visual separations, which provide for both collision and wake vortex avoidance.

Originally, the FAA designed the procedure for a 1,600 ft cloud ceiling, but implemented it to 2,100 ft. On September 21, 2012, the minimum cloud ceiling for SOIA at SFO was reduced to the original designation of 1,600 ft. When using SOIA, we expect SFO to achieve higher effective capacity during applicable weather, resulting in shorter terminal delays and fewer diversions.

Operational Performance Assessment

On average, hourly throughput at SFO increased 2.7 percent between 2008 and 2010, 3.2 percent between 2010 and 2011, and 5.8 percent between 2011 and 2012. SFO operations were at a low point in 2008, while the opposite was true for the overall trend across the NAS. In addition, even though NAS-wide operations have started to recover they have still not reached the levels observed

in 2008, while the hourly throughput at SFO increased by 11 percent between 2008 and 2012, as shown in Fig. 49.

Lower RVR Minima to Enable Dual Runway Departures

In our impact analysis, we evaluate and compare performance outcomes during the relevant conditions before and after implementation of the lower RVR minima. First, we isolated the occurrences of visibility up to ¼ sm at SFO during the typically busy hours of 0800 to 2000 between 2008 and 2012. That mileage is equivalent to 1,320 ft, but we used miles instead of feet because this is how visibility is reported. Then, we evaluated and compared actual airport throughput during such operating conditions before and after RVR minima were reduced to enable dual runway operations in January 2011.

As shown in Table 17, SFO experienced visibility of up to ¼ sm for a total of 18 hours before (2008-2010) and 21 hours after (2011-2012), the RVR minima were

Table 17 – SFO: Operations during Times with Visibility up to ¼ sm

Year	Average Hourly Throughput			Number of Hours Observed
	Departures	Arrivals	Operations	
2008	31.4	23.7	55.1	9
2010	24.4	23.7	48.1	9
2011	33	28.2	61.2	5
2012	30.6	27.8	58.4	16

reduced. Even though the average hourly departure throughput during such conditions in 2008 was higher than the one observed in 2012, high-end departure throughput during visibility of up to ¼ sm has been more

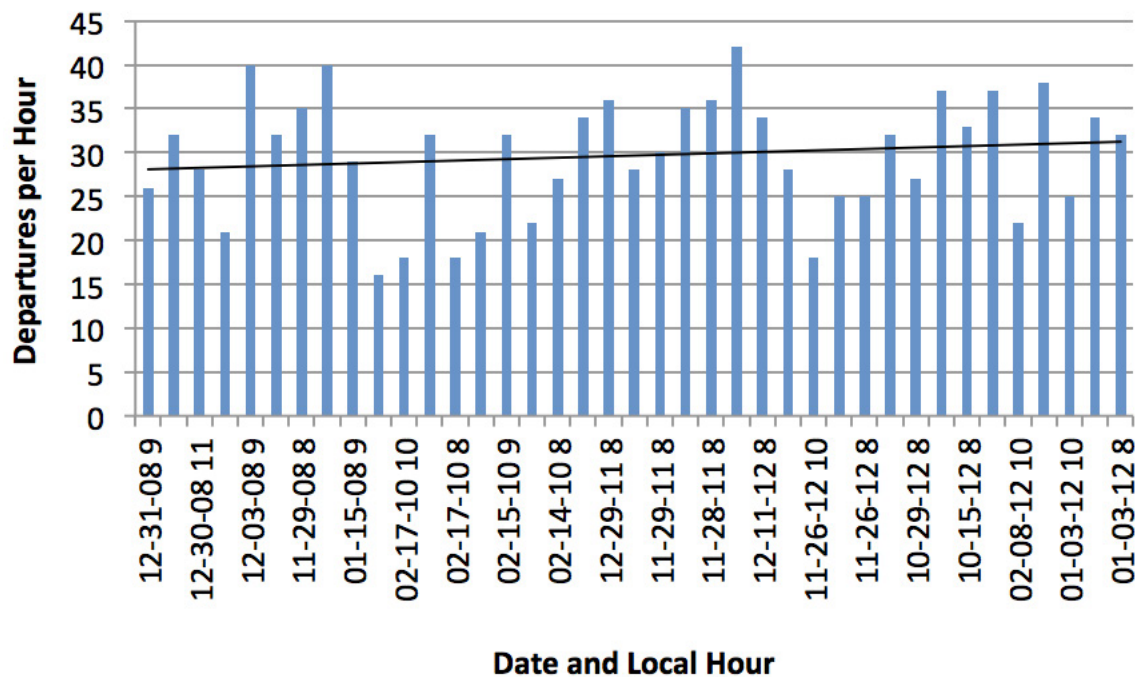


Figure 50 – SFO: Identified Lowered RVR Conditions

consistently achieved and sustained for longer periods in 2011 and 2012. As a result, as shown in Fig. 50, hourly departure throughput weighted by the actual duration of low visibility conditions increased 12 percent after RVR minima were reduced.

However, the data indicates a more significant impact on arrival throughput with accommodation of four to five additional arrivals per hour on average in 2011 and 2012. While we expected to observe a more significant impact on departure than on arrival throughput, this finding confirms operators realized access benefits at SFO and the facility exercised flexibility when managing arrival and departure flows by responding to the demand for services as needed. As a result, hourly airport throughput weighted by the actual duration of low visibility conditions was 14 percent higher after the reduction of RVR minima that enabled dual parallel runway operations.

Due to data gaps, we were not able to investigate any secondary performance impacts on departures, such as impacts on the inter-departure times, or runway queue length and delay.

Lowered Ceiling to 1,600 ft for Dual Runway Arrivals with SOIA

In our impact analysis, we evaluate and compare performance outcomes during SOIA use and past times with equivalent operating conditions. The SFO Air Traffic Control Tower facility records SOIA use in their tower logs, which they provided to us for the period between September 12, 2012 and end of March 2013.

First, we analyzed operating conditions during the hours of SOIA use and then determined hours with equivalent operating conditions between 2008 and September 2012. We focused on periods with cloud ceilings between 1,600 ft and 2,100 ft.

According to SFO Tower logs, the new SOIA minima were in use for 67 hours between September 2012 and March 2013 as shown in Table 18. Based on the actual arrival rates reported in the logs for the same hours, we estimated that 254 additional arrivals could potentially been accepted at the airport during the hours of SOIA

Table 18 – SFO: Facility Reported SOIA Use

Date	Hours Used
10/4/2012	3
10/11/2012	7
11/21/2012	1
1/5/2013	8
1/6/2013	5
1/9/2013	4
2/3/2013	1
2/5/2013	7
2/7/2013	2
2/8/2013	2
2/18/2013	14
2/19/2013	5
3/4/2013	2
3/7/2013	1
3/8/2013	5

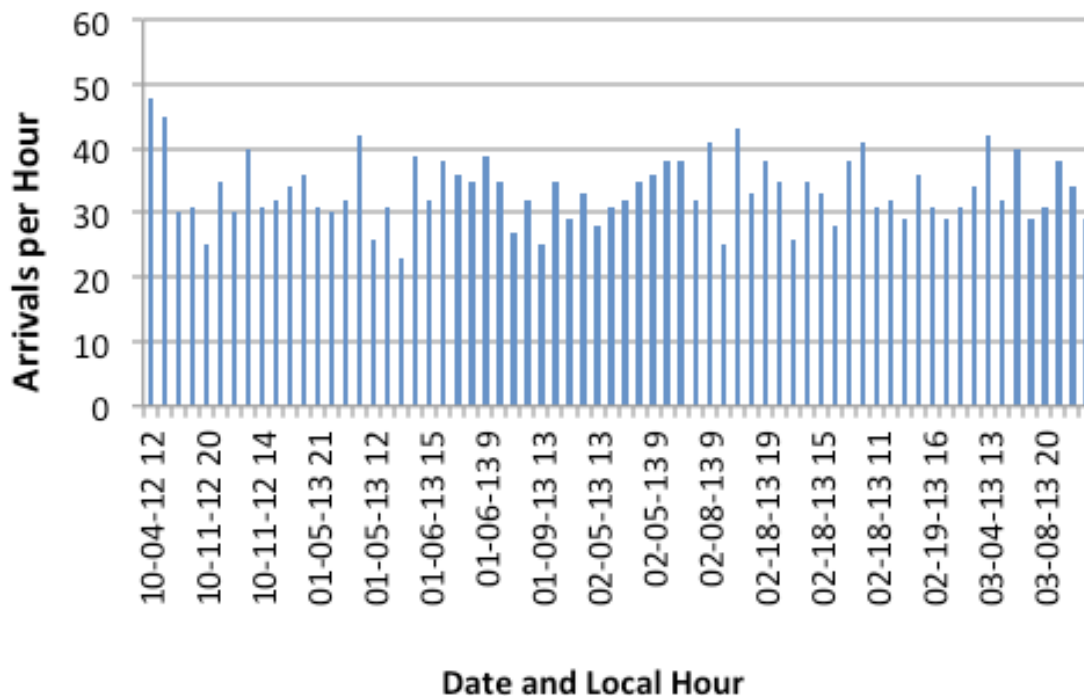


Figure 51 – SFO Arrival Counts during SOIA-use

use. We based this estimate on the Airport Arrival Rate of 30 arrivals per hour that is typical of SFO single runway operations.

In addition, on average, we observed 4.5 more arrivals per hour during the dates and times when SOIA operations were in use compared to the equivalent conditions between 2010 and March 2013 when SOIA was not in use. As illustrated in Fig. 51, performance outcomes indicate an increase in average hourly arrival throughput from 28.8 to 33.3 arrivals per hour, or 16 percent.

We investigated secondary performance impacts on efficiency of arrival terminal operations, and found significant savings in holding duration and frequency. After the implementation of the new SOIA minima, the frequency of arrivals experiencing holding delays fell from 5.6 holdings per hour to 4.3 holdings per hour, a 23 percent improvement. In addition, average holding duration was 12 minutes per flight in holding, which represents an improvement of 1 minute or 8 percent compared to the typical performance observed in the equivalent conditions between 2010 and 2012. Our analysis of other potential performance impacts, such as diversions or airport delays, produced no indication of significant changes in performance outcomes.

Conclusions

After the January 2011 reduction of RVR minima to enable SFO dual runway operations, high-end departure throughput during visibility of up to $\frac{1}{4}$ sm has been

recorded and sustained for longer periods. As a result, hourly departure throughput weighted by the actual duration of low visibility conditions increased 12 percent, and the overall airport operations rate weighted by the actual duration of low visibility conditions increased 14 percent.

Even though we expected to observe a more significant impact on departure throughput, the data indicates a more significant impact on arrival throughput. This finding confirms that operators realized access benefits at SFO and the facility exercised flexibility when managing arrival and departure flows by responding to the actual demand for services. Due to data gaps, we were not able to investigate any secondary performance impacts on departures, such as impacts on the inter-departure times, or runway queue length and delay.

Since the SOIA procedure amendment in September of 2012, SFO has been accommodating about 16 percent higher arrival throughput during the periods with cloud ceiling between 1,600 ft and 2,100 ft. Compared to the performance observed in the equivalent conditions between 2010 and 2012, the frequency of holding arrivals during adverse weather is now 23 percent lower, and the average holding delay 8 percent shorter.

It is important to emphasize that these benefits are not additive due to possible overlaps of the relevant weather conditions. Each of these benefits is a conservative estimate of the aggregated benefits, and represents a significant improvement in system and flight efficiency on its own.

Converging Runway Display Aid at Boston Logan International Airport



Terminal controllers use an automation tool known as Converging Runway Display Aid (CRDA) to help space aircraft arriving on converging runways. The tool allows controllers to easily visualize and direct a safe and efficient separation distance between aircraft arriving onto converging or intersecting runways. CRDA projects the position of a flight from one approach path onto the straight-in final approach path of the other aircraft, a practice called ghosting. Ghosting enables controllers to manage aircraft separations on both arrival flows across a wider range of weather conditions than was previously possible, increasing the airport's effective capacity in adverse weather.

Although CRDA is available in all terminal automation systems, its adaptation is site specific. Few airports have been able to implement CRDA due to the complex and costly design analysis required to address all of an airport's operational considerations. CRDA has been adapted for routine operations at Boston Logan (BOS), Philadelphia, Memphis and Newark Liberty international airports, and a few other facilities have used it intermittently to address temporary runway outages. The most recent CRDA implementation took place at BOS on September 26, 2012.

The two dominant arrival runway configurations at BOS are 4L, 4R and 22L, 27. These arrival configurations enable the airport to achieve throughput rates during Visual Meteorological Conditions (VMC) of up to 61 and

59 arrivals per hour, respectively.

As depicted in Fig. 52, Runways 22L and 27 are the primary arrival runways for flights from the North and East, while Runway 22R is the primary departure runway

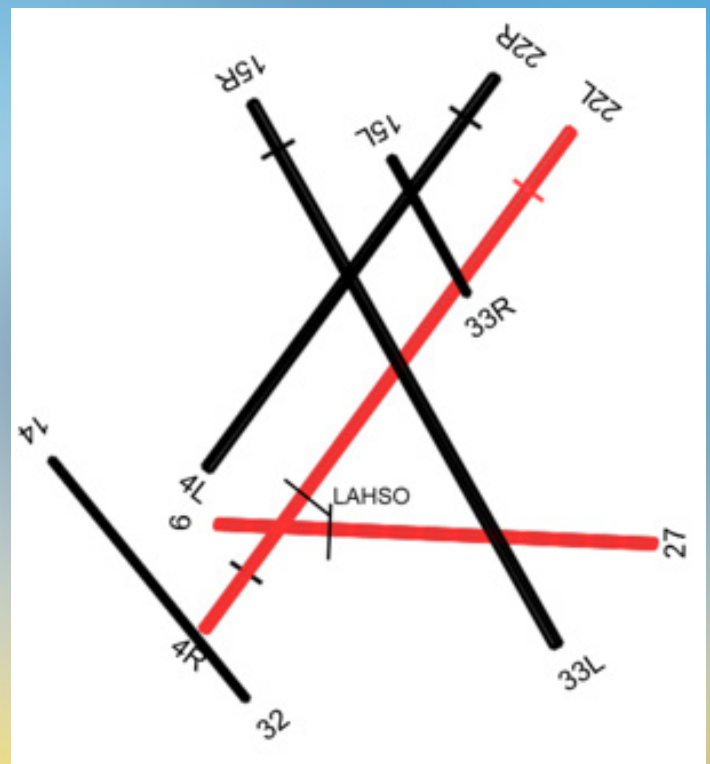


Figure 52 – BOS: Airport Configuration

Table 19 – BOS: Meteorological Condition Minima

Date	Hours Used	Visibility
VMC	≥ 2,500 ft	≥ 3 nm
MMC	< 2,500 ft and ≥ 1,000 ft	< 3 nm
IMC	< 1,000 ft.	< 3 nm

for this configuration. Runways 22L and 27 achieve arrival throughput rates of 30 and 32 arrivals per hour, respectively.

BOS uses Land and Hold Short Operations (LAHSO) on Runways 22L and 27 to achieve higher throughput rates than when using the runways individually. LAHSO is an air traffic control procedure that requires pilot participation and enables simultaneous arrival operations on two dependent converging runways. Air traffic can clear a pilot to land and hold short of an intersecting runway, an intersecting taxiway or any designated spot. Once a pilot accepts LAHSO, he or she is expected to exit the runway at the first convenient taxiway (unless directed otherwise) before the hold short point, or stop and hold at the hold short point.

Typically, LAHSO is applicable only in VMC and Marginal Meteorological Condition (MMC), if the tailwinds are not greater than 3 knots, and the runways are not contaminated. Additional site-specific restrictions may apply. Runway contamination occurs when significant rubber deposits are present, or when more than 25 percent of the runway surface accumulates over 3 millimeters of moisture in the form of rain, ice, slush or snow.

At BOS, LAHSO allows for dual runway operations of 22L and 27 in VMC and MMC as specified in Table 19. In VMC, dual runway operations provide for an effective capacity of 59 arrivals per hour. In MMC, due to the lower ceiling and the resulting increase in required separations on final approach, the effective capacity is reduced to 50 arrivals per hour.

By using LAHSO in VMC and MMC, the airport provides sufficient effective capacity to meet peak demand. However, the facility cannot use LAHSO during IMC, if tailwinds are stronger than 3 knots or the runways are contaminated. Under these conditions, the facility must use a single arrival runway illustrated in Fig. 53, reducing the effective arrival capacity to 32 arrivals per hour at best and below the level needed during the airport's busiest period. At such times, controllers often implement ground delay programs (GDP) to help the airport manage its demand.

The implementation of CRDA at BOS enabled dual runway operations of 22L and 27 during IMC and times when the tailwinds exceed 3 knots. With CRDA, BOS can now achieve an effective capacity of 38 arrivals per hour, an increase of 19 percent compared with the previously achievable rate of 32 arrivals per hour, which is sufficient to handle demand during the busiest periods and eliminates the need to implement a GDP.

This post-implementation impact analysis aimed to evaluate changes in airport and operator performance by focusing on the elimination of GDPs and increased arrival throughput during CRDA use. In addition, we

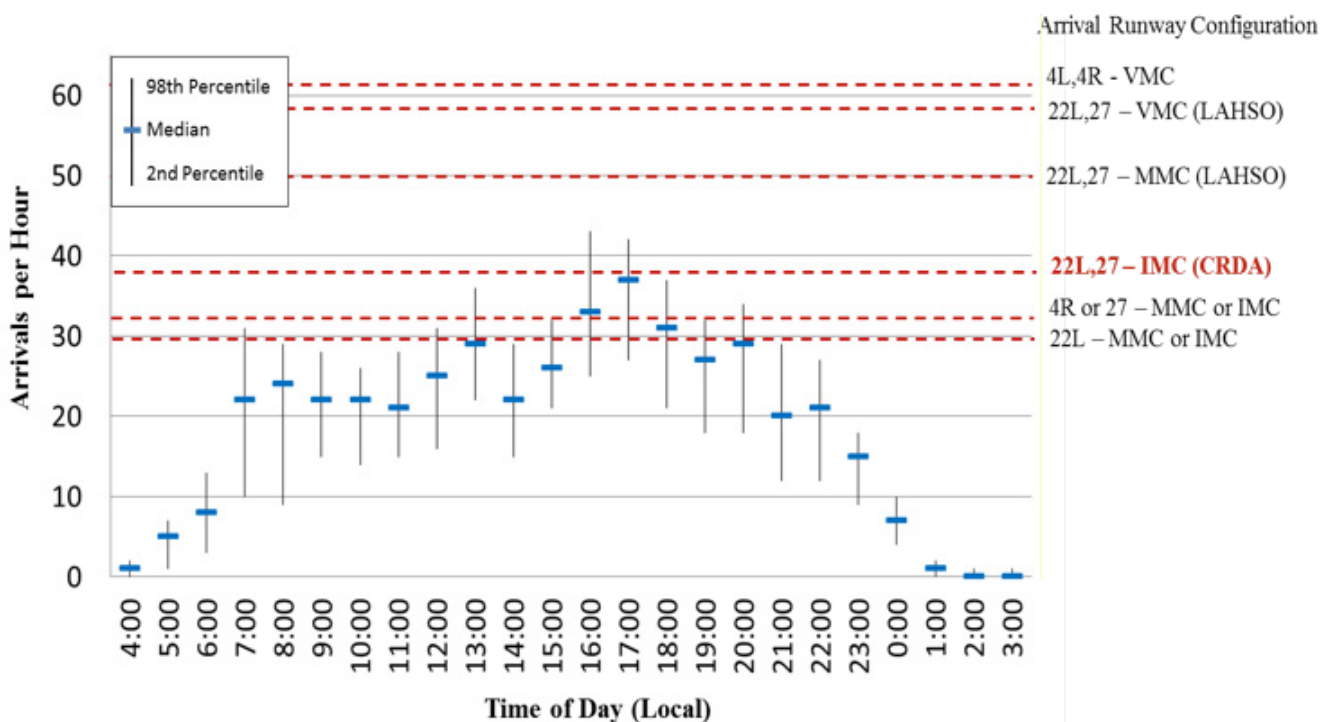


Figure 53 – BOS: Arrivals throughout the Day for FY12

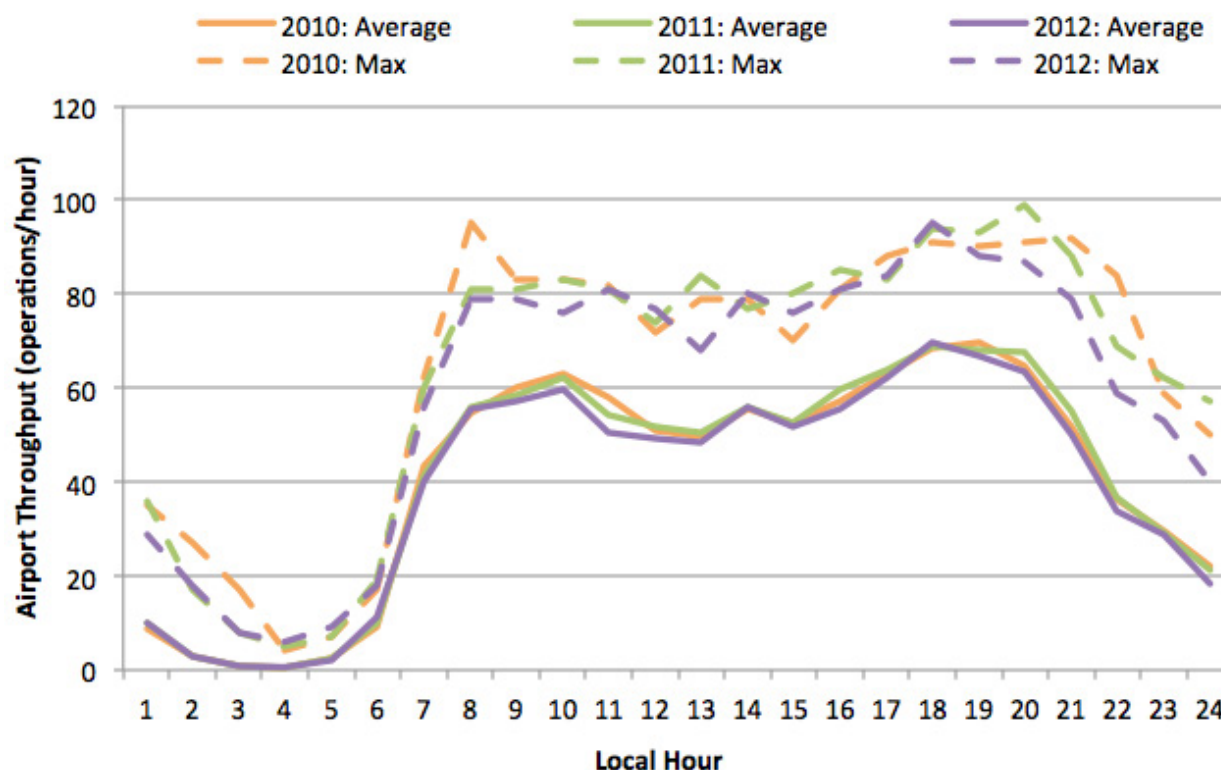


Figure 54 – BOS: Distribution of Airport Operations by Hour of Day

examined the impact on the use of the 22L, 27 runway configuration across all weather conditions.

Operational Performance Assessment

Between 2010 and 2011, average hourly throughput at BOS increased 1.6 percent, and between 2011 and 2012, it declined 3.5 percent as shown in Fig. 54. Overall, average hourly throughput at BOS decreased 1.9 percent between 2010 and 2012. While this decrease is more evident during non-peak hours, demand patterns did not significantly change. On average as well as on the high end, typical hourly distributions of arrival throughput at BOS remained the same.

As shown in Fig. 55, an analysis of the distribution of arrivals by runway during the airport's busy periods (1200 to 2000 local time) indicates no significant change in typical configurations, including the configurations used in IMC. This indicates that CRDA facilitates operations conducted during rare operating conditions by providing more efficient runway flow management and improved access. When Runway 22L was sufficient to meet the expected arrival demand in IMC on its own, it supported single runway operations more often than dual operations with Runway 27.

Actual Observations of CRDA Use

BOS TRACON provided us with examples of CRDA use between September 26, 2012 and February 27, 2013, and the corresponding actual arrival throughput rates

outlined in Table 20. To provide for controller training through a gradual increase in operational use during this period, the facility used CRDA primarily in VMC and MMC, and when LAHSO was unavailable. Once controllers become comfortable with the tool, they will use it in IMC more often.

CRDA was used nine times, totaling 23 hours in the first 5 months of its operation. It was used for 1 to 5 hours, primarily during non-IMC periods when wind conditions prevented LAHSO use. No GDP delays were recorded, and 104 arrivals were allowed to land on time or with shorter delays than would have been incurred if CRDA was unavailable.

In addition to voluntary reporting, air carriers with 1 percent or more of total domestic scheduled service passenger enplanements are required to report data for flights that involve any airport in the 48 contiguous states. This data includes Estimated Departure Clearance Time (EDCT) delays, which typically occur when a GDP is used to delay a flight on the ground at its origin to facilitate managing arrival throughput at its destination. Between September 26, 2012, and February 27, 2013, a flight into BOS that experienced an EDCT delay incurred 30.56 minutes of delay on average. If we assume that GDPs would have been used if CRDA was not available, and that each of the 104 arrivals would have incurred the average GDP delay, we can estimate that the airlines saved 53 hours in GDP delays during the first 5 months of CRDA operation.

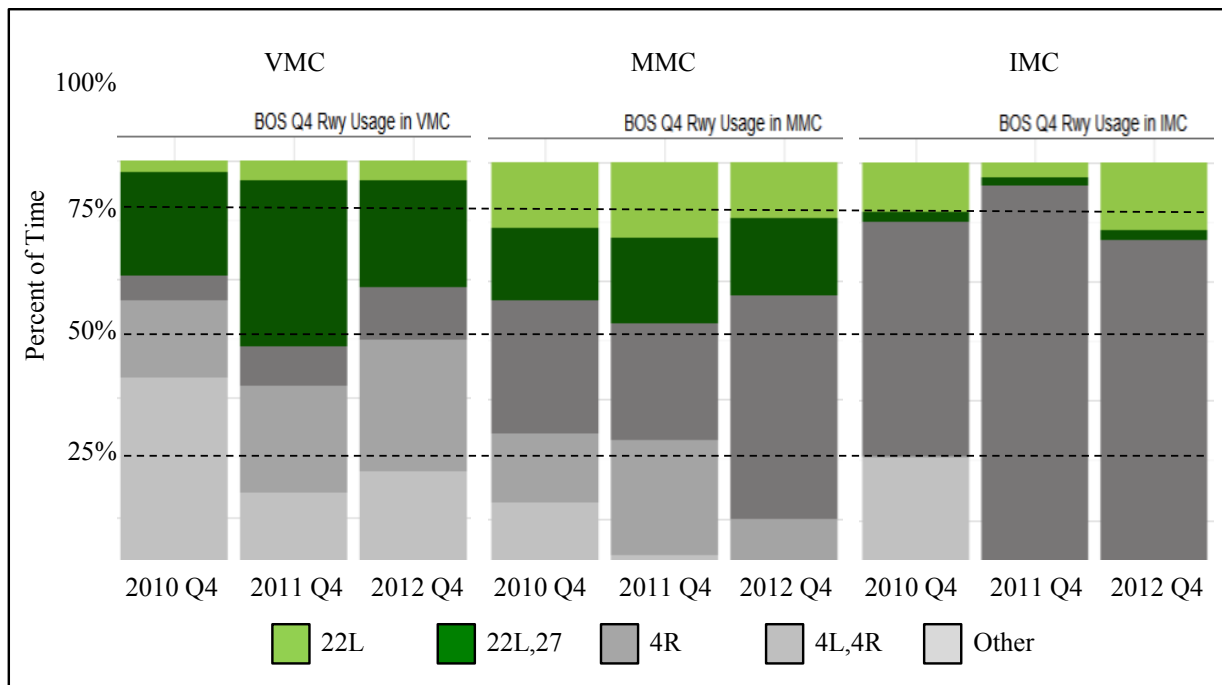


Figure 55 – BOS: Arrival Runway Configuration Use by Weather Conditions during Busy Periods

Table 20 – BOS: Facility Recorded CRDA Use

Date	CRDA Duration	Average Arrival Throughput	Additional Landings due to CRDA	VMC Time	MMC Time	IMC Time	LAHSO Infeasible due to Winds
9/30/2012	3:05	36.75	15	-	2:00	1:05	No
10/2/2012	5:00	36.4	23	3:00	2:00	-	Yes
10/7/2012	1:00	36.0	4	1:00	-	-	Yes
10/14/2012	3:00	32.0	4	3:00	-	-	Yes
11/2/2012	3:00	38.3	19	3:00	-	-	Yes
12/4/2012	2:00	36.5	9	1:30	-	0:30	Yes
12/7/2012	2:00	37.0	10	2:00	-	-	Yes
1/9/2013	1:00	39.0	7	1:00	-	-	No
2/19/2013	3:00	36.3	13	3:00	-	-	Yes
Total	23:05	36.2	104	17:30	4:00	1:35	

It is important to point out that CRDA was not designed to eliminate all but only some of the GDP delays. In fact, after its implementation, there were seven instances of GDP use that occurred through the end of 2012, and only three of these occurred when the airport was in the North East configuration and using Runways 22L or 27 for arrivals. However, we did not observe excessive tailwinds that would have forced the airport to stop using LAHSO during the seven occurrences of GDP use, and concluded CRDA mitigated this type of GDP delays during the observed period. Once the facility begins using CRDA more routinely, especially in IMC, we will see a decrease in GDPs that result in fewer delays.

Conclusions

CRDA implementation facilitates operations during rare conditions by providing more efficient runway flow management and avoiding costly GDP delays. While CRDA use is infrequent, the savings it enables are substantial.

During the 5 months after implementation at BOS, CRDA was used nine times for a total of 23 hours. This eliminated the need for GDPs for 104 flights, and resulted in an estimated savings of 53 hours of EDCT delays.

CRDA is likely to incur greater benefits by reducing GDP use and corresponding delays as facilities begin to use it on a routine basis.

Precision Departure Release Capability



Aircraft departing from an airport must merge into en route airspace traffic flows. During normal operations, there is sufficient capacity in the en route airspace to accommodate these merging departures. However, during periods of high demand, controllers often resort to a Tactical Departure Scheduling process to ensure safe integration of departures into overhead flows and enroute airspace.

Call for Release (CFR) is a tactical departure scheduling procedure used by Center controllers to address imbalances between demand and capacity. During CFR use, a Tower controller requests approval from the Center prior to releasing departures. The Tower controller manually estimates a flight's ready or wheels-off time, and verbally coordinates a time when the flight can depart with the Center controller. The Center controller uses the Traffic Management Advisor decision support tool (DST) to compute a window starting 2 minutes before and ending 1 minute after the release time, and relays it to the Tower controller. This process is not only labor intensive, but also produces imprecise release times. Manual calculations and the use of release time windows introduce uncertainty that can result in missed opportunities to merge flights into constrained en route traffic flows and, consequently, lost throughput.

Developed by NASA researchers, the Precision Departure Release Capability (PDRC) system improves tactical departure scheduling by reducing the uncertainty

of the time when a departure merges into enroute airspace.

As illustrated in Fig. 56, the PDRC system includes:

- A surface automation tool that computes ready time estimates and departure runway assignments;
- An en route scheduling automation tool that uses this information to estimate ascent trajectories to the merge point and computes release times; and
- An interface that provides two-way communications between the two tools.

To capitalize on the existing technology, minimize technology transfer issues and facilitate its adoption by the controllers, the PDRC prototype uses the Surface Decision Support System (SDSS) for the surface automation tool, a research version of the FAA Traffic Management Advisor for the en route automation tool, and a digital interface between the two DSTs to facilitate coordination.

NASA conducted three field evaluations of the PDRC concept and system at its North Texas Research Station (NTX). The first evaluation aimed to investigate concept feasibility, while the two subsequent evaluations aimed to validate the PDRC concept and investigate operational performance impacts.

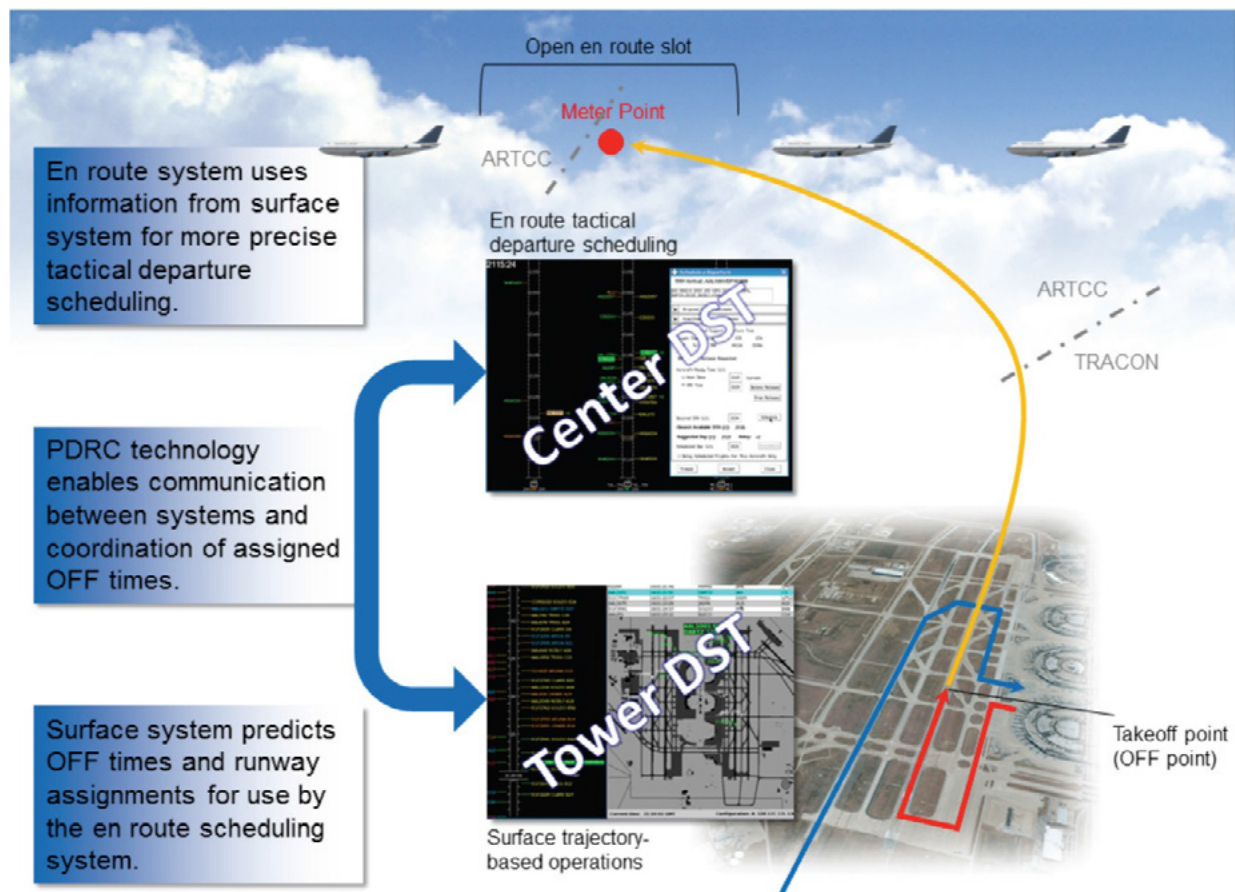


Figure 56 – Precision Departure Release Capability System Overview

The first evaluation of the PDRC prototype took place between July 13 and 29, 2011. During 12 days, NASA researchers spent 61 hours observing operations in real-time from the Fort Worth (ZFW) Air Traffic Control Center, DFW East Air Traffic Control Tower, American Airlines (AA) DFW Ramp Tower and NTX. They used Voice over Internet Protocol based audio conferencing to communicate between the different locations. On five occasions, controllers used PDRC advisories to schedule active DFW departures, and on the last day actually scheduled five departures.

During the first field evaluation, NASA collected large amount of quantitative and qualitative data in addition to demonstrating PDRC concept feasibility, later used to enhance and fine-tune the PDRC concept.

For the subsequent two operational field evaluations, Block 1 and Block 2 Operational Evaluations, NASA researchers trained numerous Center and Tower controllers, and used the NTX laboratory as the command center. The AA ramp tower was not actively involved.

Block 1 Operational Evaluation took place between April 30, 2012 and July 26 2012, and aimed to validate the PDRC concept, evaluate performance of the PDRC system, and identify and quantify sources of uncertainty

in the tactical departure scheduling process. NASA enhanced the initial PDRC system to provide improved wheels-off and airborne time estimates, and implemented a new two-way data exchange interface with American Airlines to improve gate-out time predictions. During the 13 weeks of evaluation, controllers scheduled 120 operational departures with PDRC. The enhanced PDRC system demonstrated improved wheels-off time compliance and TRACON transit time estimates. Again, NASA collected large amount of quantitative and qualitative data used to further enhance and fine-tune the PDRC concept.

Block 2 Operational Evaluation took place between November 5, 2012 and February 28, 2013. During the 16 weeks and almost 150 hours of CFR use, controllers scheduled release times for 118 operational departures, resulting in significantly improved wheels-off compliance and improved accuracy of en route entry times. Fig. 57 illustrates the key findings from the two operational evaluations that demonstrate improved wheels-off compliance compared to the baseline case.

In August 2013, NASA formally transitioned the PDRC system to FAA in a ceremony held at the FAA headquarters in Washington DC. Documents referenced below elaborate additional details about the PDRC concept, system and field evaluations.

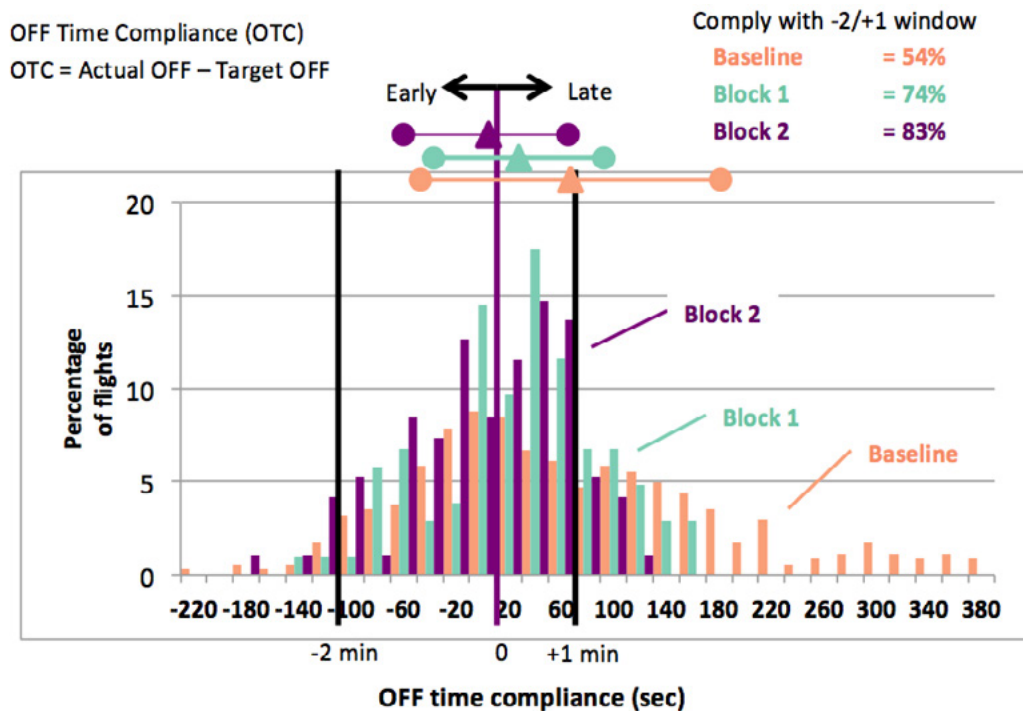


Figure 57 – Normalized absolute wheels-off time compliance for Block 1 and 2 evaluations compared to baseline data

Conclusions

Developed by NASA, the Precision Departure Release Capability (PDRC) system improves the tactical departure scheduling by reducing the uncertainty of departure en route entry time. Based on existing technology, the system includes surface and en route automation tools that improve the accuracy of wheels-off and airborne time estimates, and a two-way communication interface that enables coordination and communication of departure release times.

NASA researchers evaluated the PDRC system through three field evaluations at NASA's North Texas Research Station. The first evaluation was an initial shadow operation to investigate the feasibility of the concept. During the last two field evaluations, controllers used the PDRC to schedule 238 flights over a period of 29 weeks.

Center and TRACON controllers provided positive feedback about the PDRC system. PDRC delivered more accurate wheels-off and airborne time estimates, resulting in improved meter fix capacity management and more efficient merging of departures into the overhead enroute flows.

In August 2013, NASA formally transitioned the PDRC system to the FAA for further development and implementation.

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ACRONYMS

4D	Four Dimensional	DPL	Duplin County Airport (Kenansville, N.C.)
AAR	Airport Arrival Rate	DST	Decision Support Tool
ACM	Adjacent Center Metering	E2E	End-to-End
ADR	Airport Departure Rate	EDCT	Estimated Departure Clearance Time
AR	Authorization Required	EUF	Weedon Field (Eufala, Ala.)
ARTCC	Air Route Traffic Control Center	EUROCONTROL	European Organization for the Safety of Air Navigation
ASDE-X	Airport Surface Detection Equipment – Model X	EWR	Newark Liberty International Airport
ASOS	Automated Surface Observation System	FAA	Federal Aviation Administration
ASPM	Aviation System Performance Metrics	FY	Fiscal Year
ASQP	Airline Service Quality Performance	GDP	Ground Delay Program
ATADS	Air Traffic Activity Data System	GPS	Global Positioning System
ATC	Air Traffic Control	IAD	Washington Dulles International Airport
AWO	Arlington Municipal Airport (Arlington, Wash.)	IAP	Instrument Approach Procedure
AZ	Arrival Messages	ICAO	International Civil Aviation Organization
BOS	General Edward Lawrence Logan International Airport	IFR	Instrument Flight Rules
BVI	Beaver County Airport (Beaver Falls, Wash.)	ILS	Instrument Landing System
CAASD	The MITRE Corporation's Center for Advanced Aviation System Development	IMC	Instrument Meteorological Conditions
CDW	Essex County Airport (Caldwell, N.J.)	JFK	John F. Kennedy International Airport
CE	capable and executed	LAHSO	Land and Hold Short Operations
CFR	Call for Release	LDA	Localizer Type Directional Aid
CNE	capable but not executed	LGA	LaGuardia International Airport
CRDA	Converging Runway Display Aid	LPV	Localizer Performance with Vertical Guidance
CTZ	Clinton-Sampson County Airport (Clinton, N.C.)	MBG	Mobridge Municipal Airport (Mobridge, S.D.)
CYVR	Vancouver International Airport	MDD	Midland Air Park (Midland, Texas)
DAFIF	Digital Aeronautical Flight Information File	MEM	Memphis International Airport
DCA	Ronald Reagan Washington National Airport	METAR	Meteorological Routine Aviation Weather Report
DEH	Decorah Municipal Airport (Decorah, Iowa)	MITRE	The MITRE Corporation

MMC	Marginal Meteorological Conditions	RF	Radius-to-Fix
MRS	Minimum Radar Separations	RNAV	Area Navigation
MTN	Martin State Airport (Middle River, Md.)	RNP	Required Navigation Performance
NAS	National Airspace System	RSN	Ruston Municipal Airport (Ruston, La.)
NASA	National Aeronautics and Space Administration	RVR	Runway Visual Range
NC	not capable	SEA	Seattle-Tacoma International Airport
NDB	Non-directional Beacon	SDSS	Surface Decision Support System
NextGen	Next Generation Air Transportation System	SFO	San Francisco International Airport
NFD	National Flight Database	SID	Standard Instrument Departure
nm	Nautical Mile	SJC	Norman Y. Mineta Memorial San Jose International Airport
NOP	National Offload Program	SOIA	Simultaneous Offset Instrument Approach
NTX	North Texas Research Station	STAR	Standard Terminal Arrival
OAK	Oakland International Airport	SWW	Avenger Field Airport (Sweetwater, Texas)
OPD	Optimized Profile Descent	TAF	Terminal Area Forecast
OPSNET	Operations Counts	TBM	Time-Based Metering
PBN	Performance Based Navigation	TFMS	Traffic Flow Management System
PCZ	Waupaca Municipal Airport (Waupaca, Wis.)	TOD	Top of Descent
PDARS	Performance Data Analysis and Reporting System	TRACON	Terminal Radar Approach Control
PDRC	Precision Departure Release Capability	VHF	Very High Frequency
PDX	Portland International Airport	VMC	Visual Meteorological Conditions
PHL	Philadelphia International Airport	VOR	VHF Omnidirectional Range
PHX	Phoenix Sky Harbor International Airport	WAAS	Wide Area Augmentation System
PRM	Precision Runway Monitor	ZFW	Fort Worth ARTCC
RECAT	Wake Turbulence Recategorization Separation Standards	ZNY	New York ARTCC



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